# United States Air Force
# Scientific Advisory Board

## Report on

# Aircraft Oxygen Generation

## SAB-TR-11-04
## 1 February 2012

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# Foreword

Many aircraft make use of an on-board oxygen generation system to provide breathing oxygen for the aircrew. Compared to historical experience, there have been an increasing number of hypoxia-like incidents in the F-22 Raptor aircraft, that may be related to their on-board oxygen generating systems (OBOGS) or their installation.

The United States Air Force (USAF) Scientific Advisory Board was tasked to conduct a Quicklook Study of system safety issues involving OBOGS to help ensure that the appropriate steps are being taken to enhance flight safety of these aircraft. These included, but were not limited to, evaluating the current F-22 oxygen system, evaluating OBOGS and life support systems in general, investigating contaminants that could have an effect on OBOGS operation, evaluating human responses to high altitude rapid cabin altitude changes/rapid decompression environment with less that 90% oxygen, assisting with F-22 return-to-fly criteria as requested, revalidating and clarifying Air Standards, reviewing and validating implementation of performance-based acquisition programs and associated risk analysis protocols, examining specific hypoxia-like incidents occurring in flight regimes not normally considered likely for hypoxia events, and reviewing and revalidating all aircrew flight equipment affiliated with OBOGS-equipped aircraft. Priority was given to F-22 aircraft; however, other OBOGS-equipped aircraft were also considered.

The Aircraft Oxygen Generation (AOG) Study Panel members included those with a broad technical, acquisition/research, operational, and medical background, and included members from Industry and Academia, as well as retired military members with relevant experience. Also, the Panel received numerous inputs from the USAF Safety Center's safety investigation board members well as the F-22 Combined Test Force and the F-22 System Program Office.

The undersigned also wish to acknowledge the outstanding effort and support received from the members of the entire Study Panel, the General Officer and Senior Executive Service participants, the Air Force Safety Center and the safety investigation board members, the invited USAF, US Navy, and contractor subject matter experts, the Study Executive Officers, and the Scientific Advisory Board Secretariat staff.

Greg Martin

General Gregory S. Martin, USAF (Ret)
AOG Study Chair

George K. Muellner

Lieutenant General George K. Muellner, USAF (Ret)
AOG Study Vice Chair

## Note in Proof

After completion of the Aircraft Oxygen Generation (AOG) Quicklook Study the AOG Study Panel was made aware that the F-22 Life Support Systems Task Force has continued the testing and analysis recommended by the Study Panel and has determined what they believe to be a root cause. As this report was going to print, there are recent indications that the operation and interaction of the Breathing Regulator Anti-G valve and the pilot's life support equipment can, under certain conditions, cause a restriction to the pilot's normal breathing process. The Study Panel was recently briefed on the Task Force's findings and considers it appropriate to acknowledge this new information in order to place the contents of this Final Report of the Air Force Scientific Advisory Board's Aircraft Oxygen Generation Study in proper context.

# Executive Summary

## *Introduction*

Airborne Oxygen Generation (AOG) Systems are used on most fighter aircraft due to reduced servicing and logistics support, and safety considerations. The F-22 aircraft is equipped with such a system to provide breathing air to the pilot. This system takes engine bleed air and concentrates it to the appropriate partial pressure of oxygen as determined by the cabin altitude.

Beginning in 2008, the F-22 aircraft began to experience a significantly higher rate of hypoxia-like incidents with unknown causes as reported by the pilots. The Air Force was not able to determine the "root cause" for these incidents and a further review was recommended to the Secretary of the Air Force. The Secretary then tasked the United States Air Force (USAF) Scientific Advisory Board (SAB) to perform a Quicklook Study to cover three areas:

1. Continue the ongoing efforts to determine root cause(s), to include: Gathering data during dynamic, in-flight testing; full reviews of both the life support equipment and the aircraft's potential for passing contaminants into the cockpit and/or breathing air; and finally, to better understand the similarities and differences between the F-22 oxygen generating system and other military aircraft.
2. A better understanding of the conditions that would create hypoxia-like symptoms at altitudes not normally associated with hypoxia, along with an evaluation of the guidance associated with the breathing air standards and the human response to operating in the F-22's extraordinary flight envelope with less than 90% supplied oxygen.
3. Review the policies, processes, and procedural changes that occurred during the F-22's development and fielding, and evaluate the implications with respect to design limitations, risk analysis, program execution, and acquisition workforce.

This report provides the results of that Study.

## *Background*

Most modern day aircraft use an On-Board Oxygen Generation System (OBOGS) to provide breathing air to the crew. Beginning in the 1980s, these systems began to be chosen over liquid oxygen (LOX) systems due to reduced logistics footprint and reduced servicing requirements. These systems make use of the principal of Pressure Swing Adsorption, where cylinders of synthetic zeolite are able to concentrate the oxygen ($O_2$) output by eliminating nitrogen from the breathing gas when the cylinder is pressurized and venting the nitrogen overboard when the pressure is vented. Depending on the temperature, pressure, and cycle time, these concentrators are able to produce $O_2$ concentrations of 93-94%.

The AOG Study Panel assessed the entire force of fighter aircraft of the USAF and US Navy. With the exception of the F-15C (which continues to use a LOX system) all of the other aircraft use some form of on-board oxygen generation provided by one of two corporations that dominate this market. A review of safety incident data showed that the F-22 aircraft was the

only aircraft with an abnormally high rate of hypoxia-like incidents whose cause could not be determined. All aircraft experienced low rates of incidents caused by a hardware failure, a hose obstruction, or mask failures; however, the F-22 was the only mission design series with a high rate of unknown cause incidents.

While the pilots involved in these incidents reported a wide range of symptoms, they generally qualified as hypoxia-like. At the direction of the Air Combat Command (ACC) Commander, a Class E Safety Investigation Board (SIB) was formed to accomplish a fleet-wide assessment of oxygen generating systems and associated life support systems. This board thoroughly investigated each of the F-22 incidents of unknown cause and was unable to find a common root cause.

An F-22 was lost on a night mission in Alaska in November of 2010, and the cause was unknown when this Study was initiated. As of May 2011 the cause was still not identified, and in that month several hypoxia-like incidents at Elmendorf Air Force Base (AFB) led to the grounding of the F-22 aircraft fleet. Note: Eventual recovery of the aircraft data recorder showed the oxygen delivery system was not the cause of the aircraft loss, removing it as a primary case study for this inquiry.

With this background, this AOG Quicklook Study was initiated in June 2011. The SAB was tasked with also working with SIB members, the F-22 System Program Office (SPO), and ACC to identify necessary steps to return the F-22 to unrestricted operations. The "Return-To-Fly" section of this report defines those steps.

## Assessments

The AOG Study Panel came to the view that the hypoxia-like incidents were being caused by the F-22 life support system either (1) delivering a lower amount of oxygen to the pilot than necessary to support normal performance, or (2) the system was producing or failing to filter toxic compounds in the breathing air. In the case of either hypothesis, the result would be hypoxia-like symptoms that could threaten safety of flight.

In evaluating the system against the two hypotheses, the Panel assessed the technical performance of the F-22 life support system, the human effectiveness considerations of the system, and also the policies, processes, and procedures used to develop and acquire the system.

The technical assessment of the F-22 life support system identified the following system design. The system is pressurized by bleed air from the ninth stage of the compressor. This air is then conditioned to the right temperature, humidity, and pressure by a series of heat exchangers that use either air or polyalphaolefin (PAO) as the thermal transport medium. The air is assumed to be "breathable" when it leaves the compressor and when it enters the OBOGS cylinders. There are no filters for potential contaminants, other than 0.6 micron filters on the entry and exit of the OBOGS unit, which are designed to filter particles from the breathing air. The output is then routed to the Breathing Regulator Anti-G (BRAG) valve and on to the pilot's mask. In the F-22, the pilot always breathes under a small positive pressure. A separate valve connects the emergency oxygen system (EOS) on the ejection seat to the pilot's mask.

The system is unique in that, unlike all other OBOGS-equipped aircraft, a back-up oxygen system or plenum is not available to provide breathing continuity in the event of an OBOGS shutdown. In this situation, the pilot must manually activate the EOS, descend to an

altitude where oxygen is not required, and land as soon as possible. The EOS activation handle was found to be difficult to locate and rapidly activate. If the pilot fails to act appropriately, loss of consciousness could result, likely leading to loss of the aircraft as the F-22 aircraft does not have an automatic ground collision avoidance system (AGCAS). Additionally, the system provides delayed warning to the pilot of a failure to deliver the right partial pressure of $O_2$ and there is no indication of the pilot's oxygenation level. The system was fielded with no recurring maintenance or inspection requirements. It is a Fly-to-Warn/Fail system with servicing driven by a warning light or a pilot writing a maintenance discrepancy. (Note: The aircraft will also generate maintenance Fault Reporting Codes when the OBOGS malfunctions. These are recorded on the Data Transfer Cartridge that is downloaded after each flight.)

The Study Panel benefitted from the availability of an F-22 aircraft at the Air Force Flight Test Center that had been specially instrumented to assess the performance of the entire system providing breathing air to the pilot. This aircraft flew operational profiles to duplicate those of incident aircraft in the field. Additionally, components of incident aircraft were removed and flown on the test aircraft. Data from these sorties are shown in this report (see Appendix C). As this Study was ending, two incident aircraft from the field were brought to Edwards AFB and also instrumented.

During ground and flight tests, contaminants were found at levels well below those thought to be harmful. These contaminants contained elements of the ambient air, jet fuel, and PAO. As noted earlier, there was no contaminant filter in the breathing path. Tests have shown that the OBOGS itself can filter some elements and concentrate others, as it does with oxygen.

The assessment of the environmental control system (ECS) and life support system development programs indicated a major shortfall in the modeling and simulation of the system to determine performance under degraded conditions or in the presence of contaminants in the breathing gas. This assessment also identified major shortfalls in the application of Human System Integration (HSI) principles, availability of appropriate breathing standards, and a comprehensive understanding of the aviation physiology implications of sustained operations at high altitude without a full pressure suit.

The F-22 was developed during a period of major changes in the Air Force acquisition process. The majority of the Department of Defense military specifications and standards were rescinded and the acquisition workforce was reduced in favor of increased industry responsibility. A refined program management structure delegated many decisions to Integrated Product Teams (IPTs) for non safety-critical functions. These changes left major uncertainties as to what was an "inherently governmental responsibility." Additionally, the program underwent several major restructures driven by cost and funding constraints, to include major reductions in the size of the F-22 program office.

These assessments led the Study Panel to make the following Findings and Recommendations to both mitigate identified risks in allowing the F-22 to return to flight and to provide the data necessary to identify the root cause(s) of these hypoxia-like incidents.

## *Findings*

1. The F-22 OBOGS, Back-up Oxygen System (BOS), and EOS were not classified as "Safety Critical Items."
    - The Life Support System IPT eliminated the BOS to save weight.
    - The ECS IPT designed an Air Cycle Machine bypass to provide bleed air to the OBOGS in the event of an ECS shutdown.
    - The Emergency Oxygen System was deemed to be an adequate Backup Oxygen System.
    - The ECS IPT decided to forgo the Air Cycle Machine bypass.
    - With an ECS shutdown, the pilot's flow of breathing air is cut-off thus requiring the pilot to activate the Emergency Oxygen System to restore the flow of breathable air.
    - Interrelated and interdependent decisions were made without adequate cross-IPT coordination.

2. Over the past 20 years, the capabilities and expertise of the USAF to perform the critical function of Human Systems Integration have become insufficient, leading to:
    - The atrophy of policies/standards and research and development expertise with respect to the integrity of the life support system, altitude physiology, and aviation occupational health and safety.
    - Inadequate research, knowledge, and experience for the unique operating environment of the F-22, including routine operations above 50,000 feet.
    - Limited understanding of the aviation physiology implications of accepting a maximum 93-94% oxygen level instead of the 99+% previously required.
    - Specified multi-national air standards, but deleted the BOS and did not integrate an automated EOS activation system.
    - Diminution of Air Force Materiel Command (AFMC) and Air Force Research Laboratory (AFRL) core competencies due to de-emphasis and reduced workforce to near zero in some domains.

3. Modeling, simulation, and integrated hardware-in-the-loop testing to support the development of the F-22 life support system and thermal management system were insufficient to provide an "end-to-end" assessment of the range of conditions likely to be experienced by the F-22.
    - Engine-to-mask modeling and simulation was non-existent.
    - Dynamic response testing across the full range of simulated environments was not performed.
    - Statistical analysis for analyzing and predicting system performance/risk was not accomplished.

- Performance of OBOGS when presented with the full range of contaminants in the ECS air was not evaluated.

4. The F-22 life support system lacks an automatically-activated supply of breathable air.
   - ECS shutdowns are more frequent than expected and result in OBOGS shutdown and cessation of breathing air to the pilot.
   - The F-22 is the only OBOGS-equipped aircraft without either a BOS or a plenum.
   - The "OBOGS Fail" light on the integrated caution, advisory, and warning system (ICAWS) has a 12-second delay for low oxygen, providing inadequate warning.
   - When coupled with a rapid depressurization at the F-22's operational altitudes, the "Time of Useful Consciousness" can be extremely limited.
   - The EOS can be difficult to activate, provides inadequate feedback when successfully activated, and has limited oxygen duration.

5. Contaminants identified in the ongoing Molecular Characterization effort have been consistently measured in the breathing air, but at levels far below those known to cause health risks or impaired performance.
   - Contaminants that are constituents of ambient air, Petroleum, Oils and Lubricants, and polyalphaolefin are found throughout the life support system in ground and flight tests.
   - OBOGS was designed to be presented with breathable air and not to serve as a filter.
   - OBOGS can filter some contaminants and there is evidence it may concentrate others.

6. The OBOGS was developed as a "fly-to-warn/fail" system with no requirement for initial or periodic end-to-end certification of the breathing air, or periodic maintenance and inspection of key components.
   - Engine bleed air certified "breathable" during system development.
   - OBOGS units are certified at the factory.
   - No integrated system certification.
   - No recurring Built-In Test, inspections, or servicing.

7. Given the F-22's unique operational envelope, there is insufficient feedback to the pilot about the partial pressure of oxygen ($PPO_2$) in the breathing air.
   - Single oxygen sensor well upstream of the mask.
   - 12-second delay in activating the ICAWS when low $PPO_2$ is detected.
   - Inadequate indication of EOS activation when selected.
   - No indication of pilot oxygen saturation throughout the F-22 flight envelope.

8. The F-22 has no mechanism for preventing the loss of the aircraft should a pilot become temporarily impaired due to hypoxia-like symptoms or other incapacitating events.
    - Disorientation, task saturation, and/or partial impairment from hypoxia could result in loss of the aircraft and possibly the pilot.

9. The F-22 case study illustrates the importance of identifying, developing, and maintaining critical institutional core competencies.
    - Over the last two decades, the Air Force substantially diminished its application of systems engineering and reduced its acquisition core competencies (e.g., systems engineering, HSI, aviation physiology, cost estimation, contracting, and program and configuration management) to comply with directed reductions in the acquisition work force.
    - By 2009, the Air Force had recognized this challenge and developed a comprehensive Acquisition Improvement Plan (AIP) and an HSI plan.
    - Although the AIP has been implemented, the HSI plan is early in its implementation.
    - A clear definition of "inherent government roles and responsibilities" is not apparent.

## *Recommendations*

1. Develop and install an automatic Backup Oxygen Supply in the F-22 life support system. [Office of Primary Responsibility (OPR): ACC] [Office of Collateral Responsibility (OCR): Air Force Life Cycle Management Center (AFLCMC)]
    - Consider a 100% oxygen BOS capability unless hazardous levels of contaminants in OBOGS product air can be ruled out.

2. Re-energize the emphasis on Human Systems Integration throughout a weapon system's lifecycle, with much greater emphasis during Pre-Milestone A and during Engineering and Manufacturing Development phases. [OPR: AFMC, Assistant Secretary of the Air Force (Acquisition) ( SAF/AQ)]
    - Identify and reestablish the appropriate core competencies. [OPR: SAF/AQ] [OCR: AFMC, Air Force Surgeon General (AF/SG)]
    - Develop the capability to research manned high altitude flight environments and equipment, develop appropriate standards, oversee contractor development, and independently certify critical, safety-of-flight elements. [OPR: AFRL, AFLCMC]

3. Establish a trained medical team with standardized response protocols to assist safety investigators in determining root cause(s) for all unexplained hypoxia-like incidents. [OPR: AFLCMC, AF/SG] [OCR: AFRL]

4. Develop and implement a comprehensive Aviation Breathing Air Standard to be used in developing, certifying, fielding, and maintaining all aircraft oxygen breathing systems. [OPR: SAF/AQ] [OCR: AFMC, AFRL, AFLCMC]

5. Create and validate a modeling and simulation capability to provide end-to-end assessments of life support and thermal management systems. [OPR: AFMC]
   - The initial application should be the F-22 followed by the F-35.
6. Improve the ease of activating the EOS and provide positive indication to the pilot of successful activation. [OPR: ACC] [OCR: F-22 SPO]
7. Complete the Molecular Characterization to determine contaminants of concern. [OPR: AFRL, ACC, F-22 SPO]
   - Where appropriate, alternative materials should be considered to replace potential sources of hazardous contaminants. [OPR: Deputy Chief of Staff for Logistics, Installations, and Mission Support (AF/A4/7), AF Petroleum Agency]
   - Develop and install appropriate sensor and filter/catalyst protection.
8. Develop and implement appropriate inspection and maintenance criteria for the OBOGS and life support system to ensure breathing air standards are maintained. [OPR: ACC] [OCR: F-22 SPO]
9. Add a sensor to the life support system, post-BRAG (Breathing Regulator Anti-G), which senses and records oxygen pressure and provides an effective warning to the pilot. [OPR: ACC] [OCR: F-22 SPO]
10. Integrate pilot oxygen saturation status into a tiered warning capability with consideration for automatic Backup Oxygen System activation. [OPR: ACC] [OCR: AFMC]
11. Develop and install an AGCAS in the F-22. [OPR: ACC] [OCR: F-22 SPO]
12. Clearly define the "inherent governmental roles and responsibilities" related to USAF acquisition processes and identify the core competencies necessary to execute those responsibilities. [OPR: SAF/AQ, Assistant Secretary of the Air Force (Financial Management and Comptroller) (SAF/FM), Assistant Secretary of the Air Force (Installations, Environment, and Logistics) (SAF/IE), AF/A4/7]
13. Create a medical registry of F-22 personnel who are exposed to cabin air or OBOGS product gas, and also initiate epidemiological and clinical studies that investigate the clinical features and risk factors of common respiratory complaints associated with the F-22. [OPR: AF/SG]
14. Establish a quarterly follow-up to ensure SAB recommendations are implemented in a timely fashion or to respond to any event of significance. Note: The SAB is available for continued support if desired. [OPR: Headquarters, USAF]

## Return-to-Fly

### Near-Term:

- Implement improved access to, and ease of activation of, the EOS.
- Implement an independent post-BRAG $O_2$ sensor providing indication, warning, and recording capability.
- Field helmet-mounted pulse oximeter.
- F-22 Life Support Systems Task Force should consider installing carbon monoxide and carbon dioxide detectors in the F-22 cockpits.
- F-22 Life Support Systems Task Force should consider using a vacuum canister during maintenance engine runs and assess the contents should there be an incident.
- Leverage the National Aeronautics and Space Administration, or similar independent capabilities, to develop and implement the appropriate post-incident protocols with greater emphasis on forensic analysis of the entire life support and cabin pressurization systems.
- Analyze data gathered to determine effectiveness of the C2A1 filter for safety and data collection.
- F-22 Life Support Systems Task Force and 711th Human Performance Wing identify the need for contaminant mitigation measures for both OBOGS and cockpit breathing air.

### Long-Term:

- Install an automatically-activated Backup Oxygen System.
- Determine, through further data analysis, the need for aircraft mounted measurement and mitigation of contaminants in the breathing air.
- Develop and install an AGCAS for the F-22.

## Summary

The Air Force Scientific Advisory Board and the F-22 Life Support Systems Task Force have not yet determined the root cause(s) of the incidents, but have identified and mitigated a number of risks. While the data evaluated by this team identified minor system anomalies and a lack of robustness in the F-22 life support system's configuration, system performance exceeded pilot physiological needs.

Contaminants identified were at levels far below those known to be harmful to humans. The measures taken to protect the crews and gathering of appropriate data are providing substantive and valuable information and have narrowed the possibilities while maintaining combat capability. Continuing an aggressive approach with all F-22 ECS/OBOGS anomalies will be critical in resolving the unexplained physiological events. Implementing the Findings and Recommendations, along with the considerations presented in the Transition Operations section, should provide the F-22 with a significantly improved margin of safety and operational effectiveness.

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# Section 1: Introduction

## *Air Force Scientific Advisory Board*

*Integrity - Service - Excellence*

## Aircraft Oxygen Generation Quicklook Study

**Gen Gregory S. Martin, USAF (Ret), Chair**
**Lt Gen George K. Muellner, USAF (Ret), Vice Chair**

**January 24, 2012**

The United States Air Force (USAF) Scientific Advisory Board (SAB) was asked to conduct a Quicklook Study on "Aircraft Oxygen Generation" (AOG). Over the last twenty-five years, aircraft oxygen support systems for the crew have migrated from dilution systems using ground-serviced liquid oxygen to on-board oxygen generation systems (OBOGS) using molecular sieve oxygen concentrators. These systems significantly reduce the logistics footprint and require limited servicing between missions.

Over the 2008-2011 period, there were a number of hypoxia-like incidents of unknown cause in the F-22 aircraft that may be related to the OBOGS or its installation. Therefore, the Secretary of the Air Force requested this Study of system safety issues involving OBOGS on the F-22, and the oxygen generation systems on other aircraft, to ensure that the appropriate steps are being taken to enhance flight safety of these aircraft. The Study formally began in June 2011 and was completed at the end of January 2012. Interim status reports were provided to the Secretary of the Air Force and the Air Force Chief of Staff on July 1, 2011; to the Chief of Staff on September 2, 2011; and to the Secretary and the Chief of Staff on September 12, 2011. The final briefing was presented to the entire SAB on January 11, 2012 and was approved. A final briefing was provided to the Secretary and Chief of Staff on January 24, 2012. The final outbrief slides from the Study, with text annotations and supporting appendices, are provided.

The recommendations made are based on findings reached from information discussed and reviewed in the explanatory briefing slides included in this report, and information resources listed in the corresponding appendices.

## Outline

- **Introduction**
- Assessments
  - Engineering
  - Human Effectiveness
  - Policies, Processes & Procedures
- Return to Fly
- Findings
- Recommendations
- Transition Operations
- Summary

The USAF SAB was asked to put together a Study Panel to assist the Air Force in determining the root cause, or causes, of a number of unexplained hypoxia-like incidents in the F-22 fleet since 2008.

The conduct of this AOG Study has differed from most SAB studies, in that the Study Panel dealt with an ongoing operational challenge that is still accumulating data with regard to the F-22's life support system.

Further, as will be discussed, the Air Combat Command (ACC) established a Class E Safety Investigation Board (SIB) in January of 2011 to initiate a complete review of the F-22 life support system and the growing number of hypoxia-like incidents that started in 2008. After five months of focused investigation, the Safety Investigation Board President recommended the Secretary of the Air Force initiate a Broad Area Review of the F-22 life support system, which resulted in the SAB Quicklook Study on Aircraft Oxygen Generation.

This report will provide the background for the Study and then assessments of the key issues from an Engineering, Human Effectiveness, and Policy, Processes and Procedures perspective. These assessments provide the foundation for the Study's Findings and Recommendations, and also for the actions that led to returning the F-22 to normal operations.

## Aircraft Oxygen Generation Study: Charter

- Continue the evaluation of the F-22 $O_2$ system to include developing means to gather dynamic in-flight information to identify the root cause of reported hypoxia incidents
- Review and validate all associated aircrew flight equipment affiliated with OBOGS-equipped aircraft
- Evaluate further investigation into contaminants that potentially impact OBOGS operation and follow-on performance effects on aircrew
- Priority given to F-22 aircraft but expanding the scope to include the F-16, A-10, F-15E, B-1, B-2, CV-22, T-6, F-35, F-18 and other aircraft
- Examine those incidents that are occurring in flight regimes which are normally considered unlikely for a hypoxic event (e.g., 8000' cabin attitude pressures)
- Revalidate and make recommendations to clarify guidance for Air Standards with specific guidance on effect of systems designed to minimum acceptable standards
- Direct and evaluate, if able, human response to high altitude, rapid cabin altitude changes and rapid decompression with less than 90% supplied $O_2$
- Review and validate the implementation of performance based contract acquisition programs and risk analysis protocols
- Evaluate OBOGS, and life support systems in general, to determine commonalities and acquisition philosophy across MDS and ID design limitations or key assumptions

This Study was initiated because the Air Force had been unable to determine the cause of a number of sporadic hypoxia-like incidents that were reported by F-22 pilots over the past several years.

As a result of the normal Air Force safety investigation procedures used for each hypoxia-like incident that occurred from 2008 until the present, as well as the extensive efforts of the Class E SIB initiated in January 2011, the SAB AOG Study Charter was quite specific and detailed about the Study Panel's task. Of note was the need to conduct in-flight tests and other data gathering to determine root cause, or root causes. The Charter guided the AOG Study Panel to cover three areas:

1. Continue the ongoing efforts to determine root cause(s), to include: Gathering data during dynamic, in-flight testing; full reviews of both the life support equipment and the aircraft's potential for passing contaminants into the cockpit and/or breathing air; and finally, to better understand the similarities and differences between the F-22 oxygen generating system and other military aircraft.
2. A better understanding of the conditions that would create hypoxia-like symptoms at altitudes not normally associated with hypoxia, along with an evaluation of the guidance associated with the breathing air standards and the human response to operating in the F-22's extraordinary flight envelope, with less than 99% supplied oxygen.

3. Review the policies, processes, and procedural changes that occurred during the F-22's development and fielding, and evaluate the implications with respect to design limitations and risk analysis.

The Terms of Reference for this Study are summarized above. The full AOG Study Terms of Reference are provided in Appendix I of this report.

## AOG Study Team

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Maj Brian Stahl, USAF
Maj Ryan Maresh, USAF
Capt Andrew Anderson, USAF
Mr William Quinn

The membership of the USAF SAB AOG Quicklook Study is listed above. In addition to the AF SAB Study Panel members and consultants, there was General Officer, Air Force Air Staff, and Air Force Safety Center representation. Additional information on Study Panel members is presented in Appendix J.

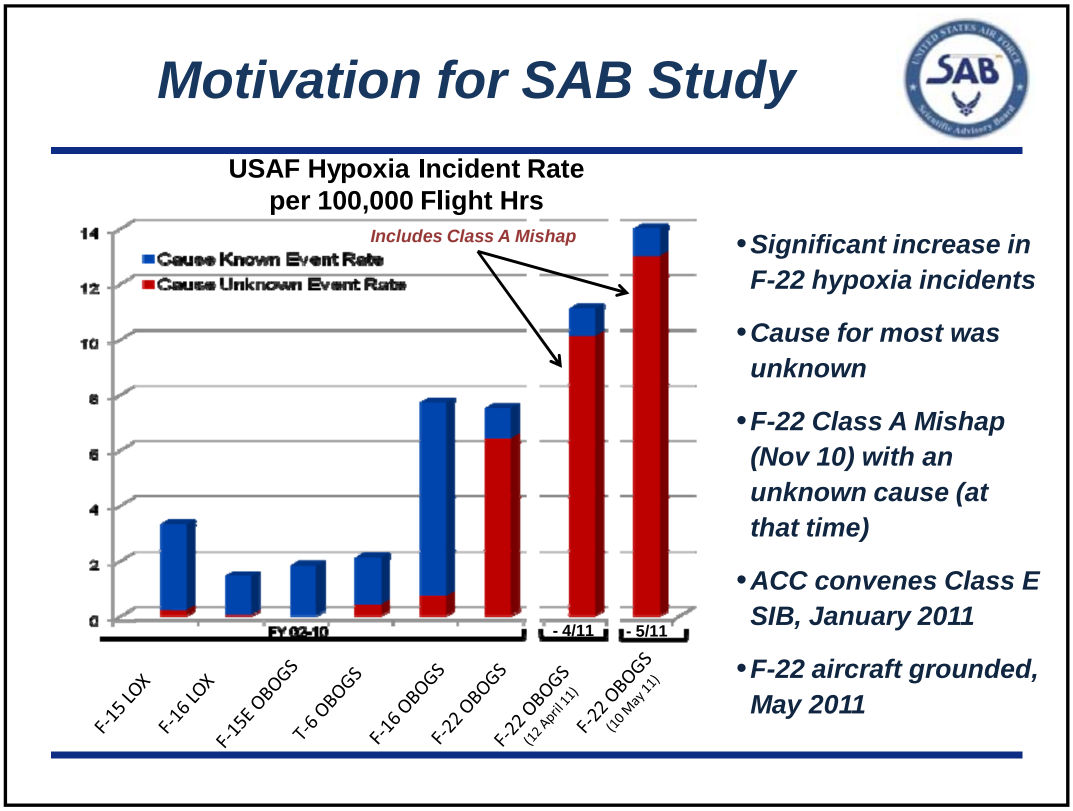
The Study Panel was ably assisted by SAB Secretariat support staff and volunteer executive officers from Office of the Assistant Secretary (Acquisition), the Air Force Flight Test Center, and the USAF Academy. The Study Panel is indebted to these individuals for their dedication and hard work in support of the AOG Study.


The AOG Study Panel received a large number of briefings and perspectives on various aircraft OBOGS standards and designs in general; the F-22 and F-22 OBOGS in particular, pilot physiological performance under various conditions, and many other related issues in the course of the Study, from within and outside of the United States Government. The Study members visited several Air Force bases and facilities, including the AF Flight Test Center at Edwards Air Force Base (AFB), California, the 1st Fighter Wing at Langley AFB, Virginia, and the Aeronautical Systems Center at Wright-Patterson AFB, Ohio.

The Panel received briefings from the Air Force Safety Center, the F-22 Combined Test Force, the F-22 System Program Office (SPO), the F-35 Joint Program Office, and the USAF School of Aerospace Medicine. In addition, inputs were sought from current and past F-22 System Program Directors and F-22 Program Chief Engineers.

The Study Panel members benefitted from hearing from the contractors that are responsible for the F-22 and its systems, or who had other useful information to offer including Lockheed Martin, Boeing, Pratt and Whitney, Cobham Mission Systems, and Honeywell. The Panel members also benefitted from hearing from representatives from the Naval Air Warfare Center and the Naval Air Systems Command, as well as the National Aeronautics and Space Administration's (NASA) Dryden Flight Research Center and Johnson Space Center.

A more detailed listing of the contributing organizations and experts is included in Appendix K.




The Secretary of the Air Force's reason for requesting the SAB Study is reflected in this slide. As the slide reflects, the F-22 had a higher hypoxia incident rate than other fighter aircraft. Of more concern was the fact that the majority of the F-22 incidents could not be traced to a known cause or system failure.

An F-22 was lost on a night mission in Alaska in November of 2010, and the cause was unknown when this AOG Study was initiated. As of May 2011, the cause was still not identified, and in that month several hypoxia-like incidents at Elmendorf AFB, Alaska led to the grounding of the F-22 aircraft fleet. Eventual recovery of the mishap aircraft's data recorder showed the oxygen delivery system was not the cause of the aircraft loss, removing it as a primary case study for this inquiry.

Following the mishaps in Alaska, ACC convened a Class E SIB focused on a fleet-wide assessment of oxygen generating systems and associated life support systems with emphasis on the F-22. A Broad Area Review was considered following the SIB; however a decision was made to engage in this SAB Study.

## Hypotheses

1. The F-22 oxygen delivery system is failing to deliver adequate $O_2$ to the pilot, resulting in hypoxia symptoms that threaten safety of flight

2. The F-22 oxygen delivery system is either producing or failing to filter a toxic compound(s) in the $O_2$ to the pilot resulting in hypoxia-like symptoms that threaten safety of flight

The AOG Study Panel came to view that the hypoxia-like incidents were being caused by the life support system either (1) delivering a lower amount of oxygen to the pilot than necessary to support normal performance, or (2) the system was producing or failing to filter toxic compounds in the breathing air. In either case, the result would be hypoxia-like symptoms that could threaten safety of flight.

Each of these two main hypotheses had six sub-hypotheses, along with a series of questions that guided the Study effort. Later in this report a slide presents the essence of the sub-hypotheses and what has been learned, thus far, with regard to proving or disproving them, and what actions are being taken to mitigate the risks.

A large number of hypotheses and sub-hypotheses were developed by the AOG Panel in the course of its inquiry. As they were developed and refined each was analyzed and responses provided by a technical team led by the F-22 SPO. The hypotheses and the detailed discussion/response for each, as prepared and presented by the technical team led by the F-22 SPO, are contained in Appendix H of this report.

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## Section 2: Assessments

### Outline

- Introduction
- **Assessments**
  - Engineering
  - Human Effectiveness
  - Policies, Processes & Procedures
- Return to Fly
- Findings
- Recommendations
- Transition Operations
- Summary

As the AOG Study Panel formed up, it was organized to approach the Terms of Reference along an assessment methodology that considered (1) engineering and technical aspects of the F-22 OBOGS, as well as comparisons with other Department of Defense (DoD) aircraft equipped with an OBOGS; (2) the set-up of the system with regards to how well it contributed to the human effectiveness of the crews operating the F-22 (including human systems integration, toxicology, and modeling and simulation; and (3) the implications of the policies, processes and procedures used to develop, field and sustain the F-22 and its life support system.

As a result of the initial assessments of a fatal F-22 mishap in Alaska in November 2010, and two incidents that occurred at Elmendorf AFB in early May 2011, the F-22 was grounded and great attention was focused on testing many of the components contributing to the F-22's life support systems. Once the SIB had determined that they understood the components' performance characteristics, a specific protocol was established for conducting a series of dynamic, in-flight tests to ensure the accurate data collection from a system performing in an end-to-end fashion. Until that point, the Air Force had not tested and measured the F-22 life support system end-to-end—either in a comprehensive modeling and simulation environment or in the air with a specifically instrumented aircraft.

Building on the lessons of the SIB and the data gathered during the dynamic in-flight testing conducted on a specially-instrumented test aircraft at Edwards AFB, the Study Panel developed a comprehensive "Return-to-Fly" program that will be detailed further in a few subsequent slides. This program was designed after a statistical assessment indicated that as the test sorties were being flown, it was quite unlikely that another hypoxia-like event might occur, and therefore, determining the root cause(s) could be highly problematic until many more sorties were flown. With that in mind, the Study Panel determined that a carefully planned "Return to Fly" program could be developed that would "Protect the Crews" and "Continue to Collect" data, and suggested the Air Force form a "Task Force" team to ensure a standard approach in gathering and analyzing the data for each incident that might occur during this phase.

Since initiation of the Return to Fly program in mid-September 2011, the Air Force flew about 7,000 sorties as of the date of this report. A discussion of what Breathing Air Anomalies have occurred follows.

From the data gathered to date, the Study Panel believes it has been able to properly narrow the field of potential causes for the hypoxia-like incidents, such that the Task Force and continuation of the SIB efforts will be able to eventually determine the root causes by reviewing the Study Panel's Findings and implementing its Recommendations. But in addition to dealing with the Findings and preparing to implement the Recommendations, the Study Panel has made a series of suggestions to the Task Force regarding the transition from the "Return to Fly Phase" to the "Normal Operations" phase for F-22 operations.

## Outline

- Introduction
- **Assessments**
  - **Engineering**
  - Human Effectiveness
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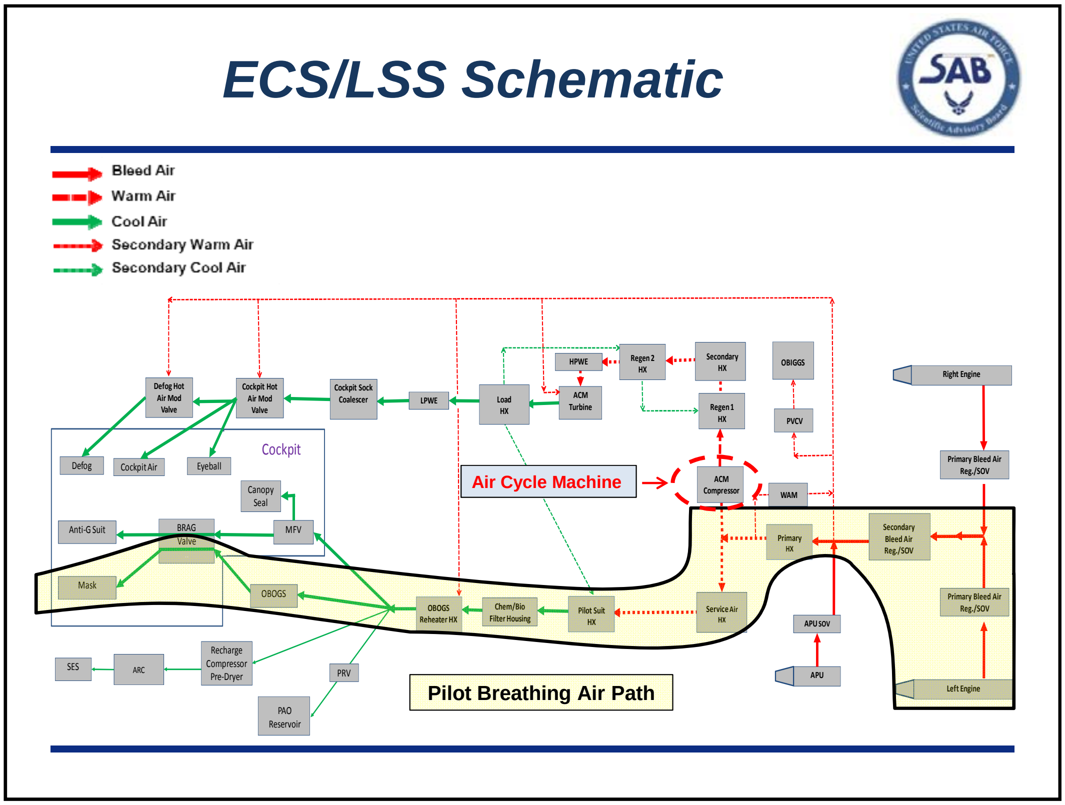
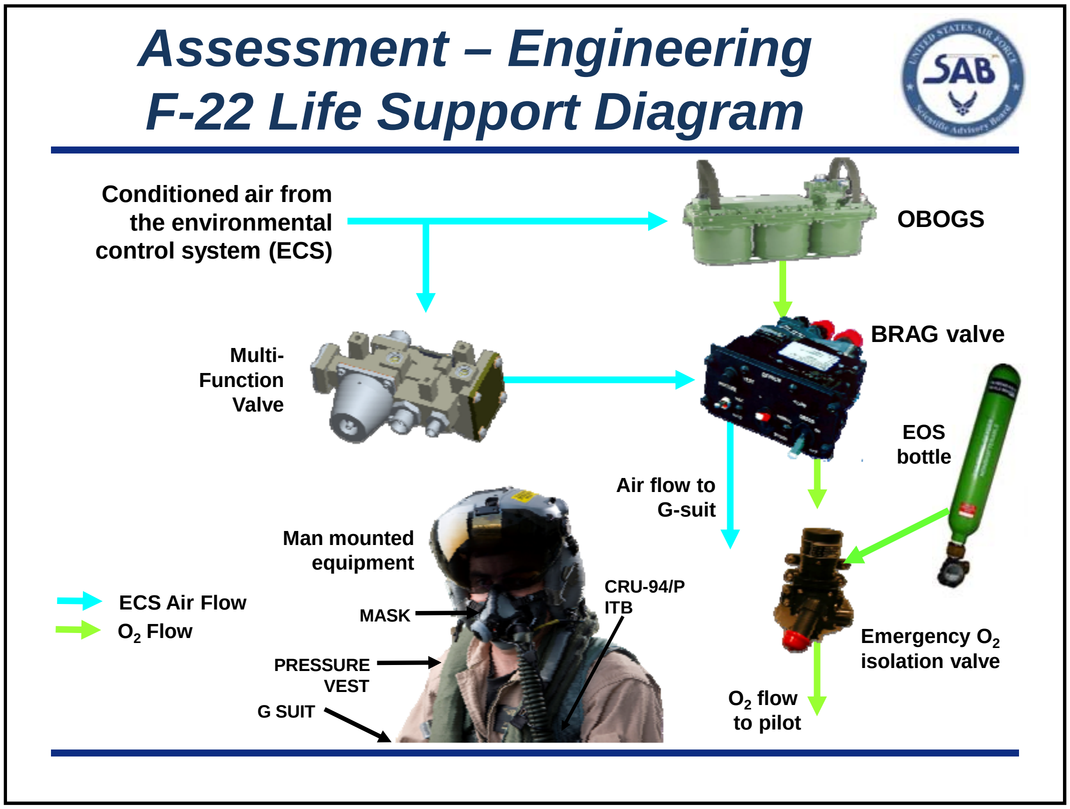
The AOG Study Panel looked at several engineering/technical areas in the course of the Study. The following slides present the main technical areas reviewed and the Panel's observations regarding the F-22 Environmental Control System (ECS) / Life Support System (LSS) and the initial safety / design approaches that were employed during system development, use of modeling and simulation, and the scheduling of the F-22 OBOGS product.




This slide shows the schematic for the F-22 ECS/LSS. The LSS is powered by bleed air from the ninth-stage of the F119 engine's compressor, or from the auxiliary power unit (APU) on the ground. The air is then conditioned to the proper pressure (35 pounds per square inch (psi)), temperature, and humidity by heat exchangers that have polyalphaolefin, a synthetic lubricant used as a coolant, or air as a thermal transport medium. The Air Cycle Machine (ACM) prioritizes the bleed air flow to Life Support and Avionics cooling.

The bleed air entering the OBOGS unit is assumed to be breathable (i.e., free of harmful contaminants) as the air handling and coolant systems are each self-contained systems, with the contents of each never coming in direct contact with the other. The quality of the breathing air was tested and certified at the ninth-stage bleed port on engine qualification during the F-22 Engineering and Manufacturing Development (EMD) phase. Individual engine bleed air is not tested on engine delivery or in recurring maintenance. The system contains no filter designed to remove potential contaminants in the breathing air. Initially, the system was designed with a chemical-biological filter, but it was removed during EMD. The OBOGS unit has an inlet filter (0.6 micron) that is designed to filter particles. In testing, the OBOGS unit demonstrated the ability to filter some contaminants while concentrating others.

A single sensor schedules the OBOGS cycles to respond to inputs from the cabin altitude sensor and provides system warning to the F-22's Integrated Caution, Advisory, and Warning System (ICAWS) when the oxygen production is below a software-defined warning band for 12 seconds. A complete analysis of the entire system is limited by the inability to model the flow process from the engine's Bleed Air Port to the pilot's mask.



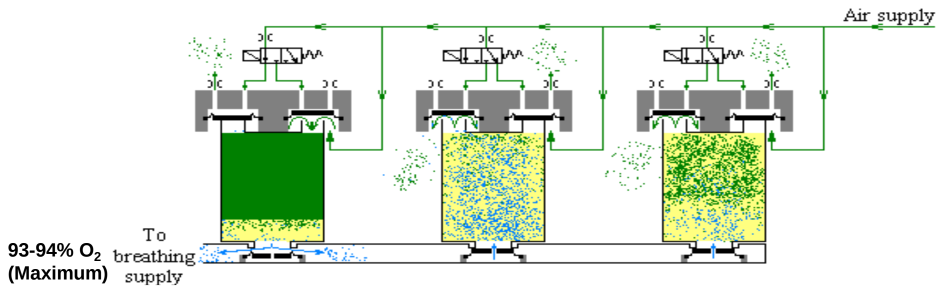

This slide diagrams the F-22 Life Support System starting with the conditioned air from the F-22 ECS. The system requires engine bleed air that is properly conditioned to the right pressure, temperature, and humidity. Unlike most other aircraft oxygen generation systems, the breathing air to the F-22 pilot is not diluted with cockpit air to obtain the appropriate oxygen partial pressure ($PPO_2$) necessary to maintain physiological function at a particular altitude, but rather it is concentrated to the necessary $PPO_2$ by controlling the cycling of the OBOGS. Also unlike other aircraft, the F-22 pilot is always breathing under a positive pressure (about 1 psi on the ground).

Another difference between the F-22 and other existing systems is that the F-22 does not incorporate a Post-OBOGS Back-up Oxygen System (BOS), Standby Oxygen System, or a plenum (air reservoir) to provide breathing continuity while dealing with an OBOGS shutdown. With a shutdown of the F-22 OBOGS, the pilot must activate the F-22's Emergency Oxygen System (EOS), which provides a limited (5-20 minutes) supply of 100% oxygen to the pilot.

The F-22 originally included a self-regenerating Standby Oxygen System, now called BOS, but it was removed as a weight-saving measure during development. The logic behind the decision was that the EOS provided adequate back-up in the event of an OBOGS shut-down. That decision saved approximately 15 pounds and was approved by the F-22 Life Support System Integrated Product Team (IPT) in 1992. This decision was made based on the availability of the EOS and the expectation that OBOGS shutdowns would be an unlikely occurrence. Additionally, the ECS IPT was designing a bypass of the ACM that would ensure the OBOGS received bleed air if ECS system failure occurred. This modification was not incorporated and ECS shutdowns have occurred more frequently than was anticipated.

Output from the OBOGS flows to the Breathing Regulator Anti-G (BRAG) valve where it is provided to the pilot's mask at the proper pressure. This valve also regulates flow to the anti-G vest. A separate isolation valve routes the emergency oxygen to the pilot's mask when the EOS is activated. When the EOS is consumed, the pilot will revert to OBOGS output if the system is functioning.

## Assessment – Engineering OBOGS Schematic Diagram

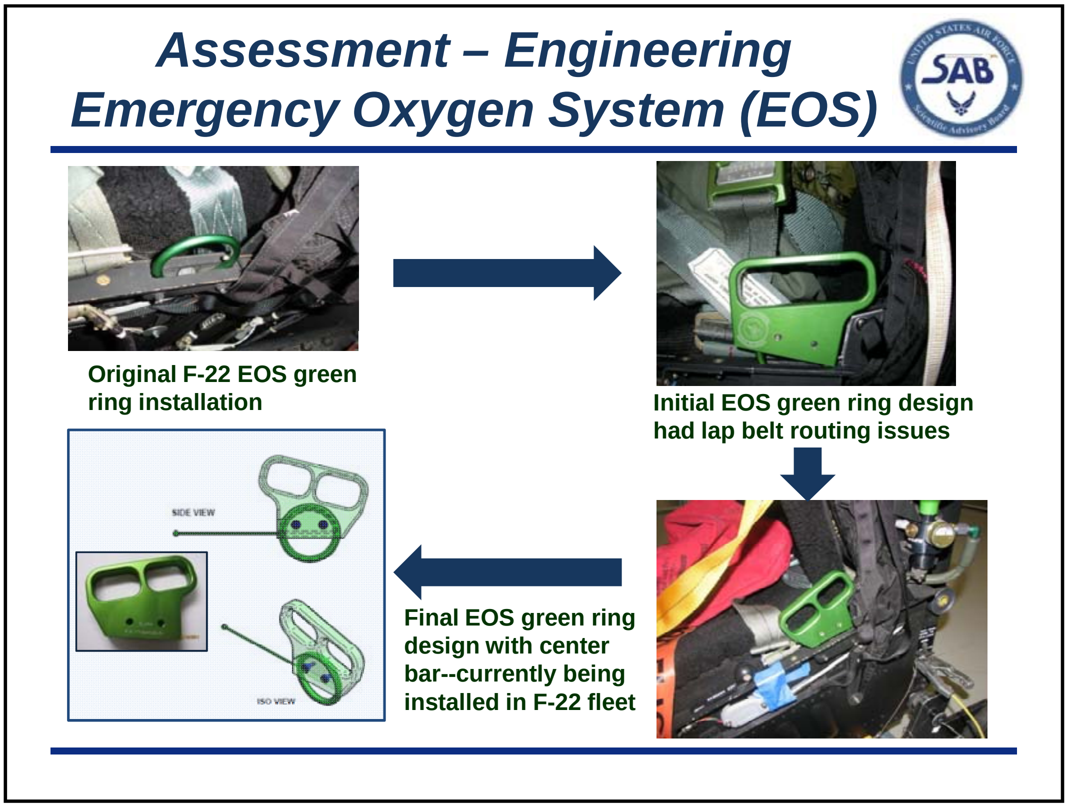



- Efficiency Factors: Temperature, Pressure, Affinity
- Internal Dilution Control
- Not Designed as a Filter

This slide shows the schematic for the F-22's OBOGS. The F-22 OBOGS consists of three molecular sieve canisters that incorporate 13X zeolite, a synthetic zeolite that absorbs nitrogen from the bleed air, thereby producing oxygen-rich breathing gas. The OBOGS has a 0.6 micron filter on the inlet and exit ports designed to filter particles; however, the system contains no filter designed to remove potential contaminants in the breathing air. Zeolite has been shown to filter some contaminants and concentrate other chemicals such as argon. Argon in this case is not a contaminant, but rather it is a normal constituent of air that is concentrated, like oxygen, when nitrogen is removed.

The F-22 OBOGS does not always produce oxygen at its maximum rate, but rather concentrates oxygen from engine bleed air to obtain the appropriate $PPO_2$ necessary to maintain physiological function at a particular altitude. OBOGS performs the concentrating function by controlling the length of the concentration cycle—a shorter charge cycle and a longer vent cycle produces a higher concentration of oxygen. The F-22 system modulates the cycling of the three zeolite canisters to produce a continual flow of breathing air at the proper $PPO_2$, as determined by cabin altitude. System performance is dependent on pressure differentials across the zeolite bed, with the input pressure regulated to 35 psi and the outlet pressure to 30 psi. In the F-22, if the ECS shuts down the bleed air flow to the OBOGS, the pilot becomes starved of air, which requires activation of the EOS and curtailment of the mission. As noted previously, the F-22 BOS was traded away as a weight-saving measure on the assumption that bleed air would always be available. All other OBOGS-equipped aircraft life support systems incorporate a BOS or plenum downstream of the OBOGS unit to provide breathing continuity in the event of an OBOGS shutdown for some period of time. The 1992 Trade Study determined that the EOS,

located on the ejection seat, was adequate as a back-up. This was highlighted on the previous slide.




### *Emergency Oxygen System*

The primary purpose of an emergency oxygen system is to provide breathing air in the case of ejection. Since the emergency oxygen system in the F-22 was identified as an adequate back-up in the event of OBOGS shutdown, it is essential that the pilot can easily and rapidly activate the EOS. This is critical as OBOGS shutdowns require rapid activation of the EOS and is especially critical in rapid decompression situations. As originally designed, the EOS was determined to be difficult to activate due to the small ring size of the activation handle, high activation forces required to pull the handle, and a two-step activation process. EOS activation proved to be even more difficult when the pilot is wearing winter flying gear. In addition to these difficulties, once activated, the EOS provides inadequate positive feedback of successful activation to the pilot.

Shown above is the current modification of the EOS handle to make it easier to locate and pull in high-stress situations. This modification is currently being installed into the F-22 fleet.

### *ECS Modeling and Simulation*

Major F-22 systems were included in the F-22 Vehicle System Simulator program. The program had dedicated hardware and/or software systems in the loop and extensive

instrumentation identical to the systems in the test aircraft. However, the ECS and oxygen generation system were not included in the F-22 Vehicle System Simulator program due to budgetary constraints.[1]

The F-22 operational life support system and the thermal management system are highly integrated with the ram air and bleed air systems of the aircraft. The complexity of the systems required to meet the demands for breathable air and electronics cooling in a rapidly changing environment of temperature, static and dynamic pressure, and aircraft acceleration has resulted in highly instrumented flight tests being the only recourse for end-to-end system performance testing and diagnostic data gathering. The presence of the human as an integral element of the platform performance, depending critically on the breathable air system, adds a major degree of complexity and source of variance in evaluating system performance, particularly when there may be contaminants present in the air system.

Computational fluid dynamics and other modeling techniques have shown significant potential for tools to model the F-22 systems. When components of a system were judged to be too complicated to model mathematically, hardware-in-the-loop testing has been an accepted method in the aerospace industry for over sixty years, when it was essential to verify the predicted performance of the sub-system before flight tests. Certain elements of the OBOGS might fall into this category in describing the performance of the molecular sieve in the presence of wide pressure fluctuations and contaminated air. Producing the proper environmental conditions on the ground to properly conduct an end-to-end test of the system will be a major challenge, but in the long run should be significantly more cost effective than relying only on flight test data.

Individual elements of the F-22 life support systems have been modeled with varying degrees of fidelity, but there has been no complete end-to-end modeling of the system either statically or dynamically over the full range of experienced flight conditions. This results in an inadequate database to predict or trouble-shoot anomalies in system performance. The combination of highly instrumented flight tests and end-to-end breathing, environmental control, and electronics cooling system ground testing with integrated hardware-in-the-loop system simulation capability would give an important degree of assurance of F-22 system performance and form the evaluation and test basis for the next generation of aircraft.

Existing models of environmental control/thermal management systems are proprietary steady-state models that are limited to mission point performance analysis. Dynamic and transient modeling of thermal components is required to conduct time-domain, continuous mission, thermo-analysis of steady-state and transient behavior to optimize the next generation aircraft environment control/thermal management systems. A key aspect of the development of this capability is a toolset that is open source. The Air Force Research Laboratory has developed a toolset that includes a library of physics-based models of system and sub-system components and a library of fluid properties and data capable of supporting the development of the dynamic numerical models and simulation of system transient behavior.

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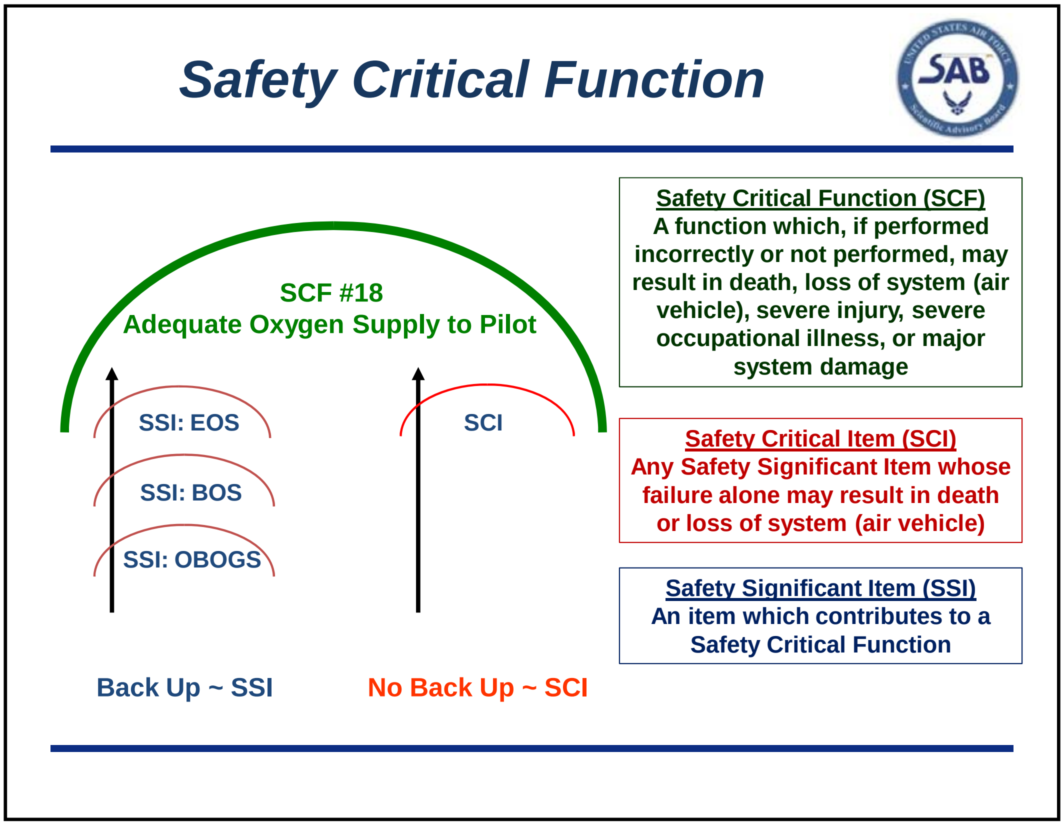
[1] Javorsek, D., et. al. "F-22 All Weather Fighter: Recent ECS Testing Results."

At the present time, no comprehensive numerical model can describe the physiologic consequences of changes in operating conditions and the performance of life support systems employed in modern high-performance aircraft. Several tentative computer models of components required to implement an integrated model of the pilot's breathing system have been created, but a fully validated model does not exist.[2,3] Such a model could be used to simulate the function of the hardware and the pilot's physiological and cognitive response to environmental changes. Although existing physiological response data may be adequate for the development and validation of such an integrated model, existing data describing the effects of the reduced oxygen and high aircraft acceleration on the pilot's cognitive ability remain inadequate for the development.

2 Bomar, J., et. al. "Modeling Respiratory Gas Dynamics in the Aviator's Breathing System (AL/CF-TR-1994-0047-Vol. 1)."

3 Bomar, J. "Modeling PBA Gas Dynamics."



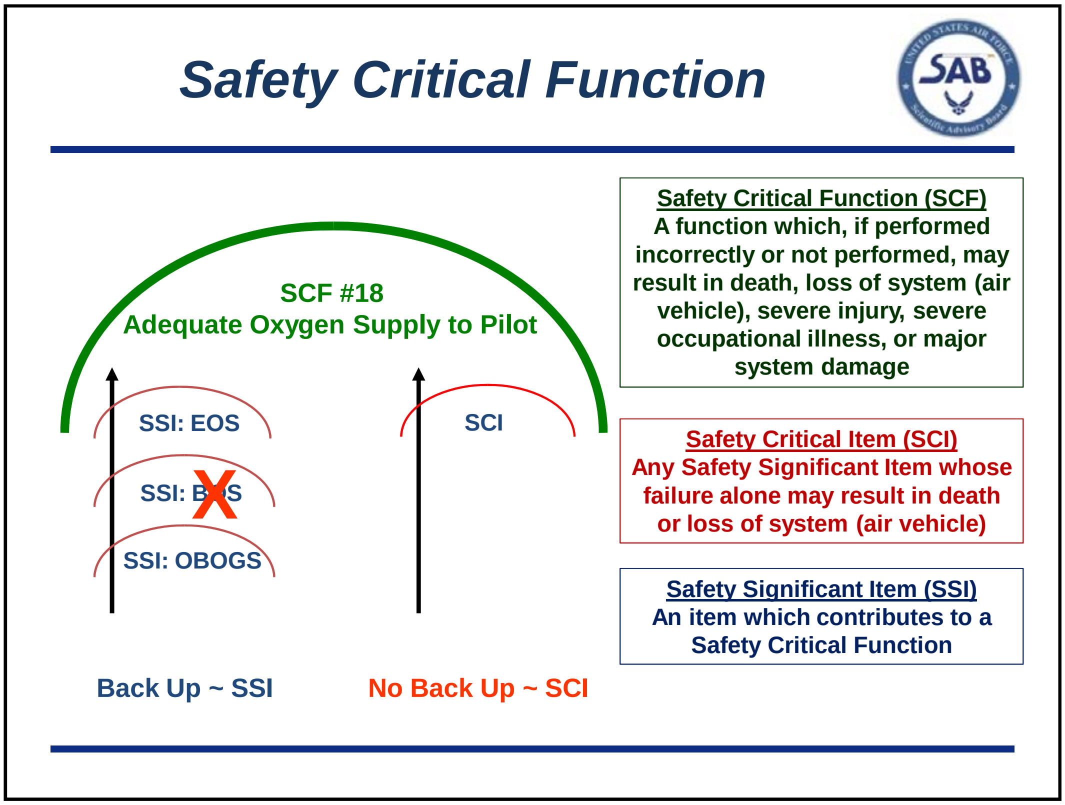

The Safety Critical Function process[4] for the F-22 program was created as a process tool for the program to use to identify the safety criticality of both hardware and software items on the aircraft. The complexity and fully integrated nature of the F-22 demanded an extensive process because hardware and software issues are highly likely to impact several other systems and subsystems. The process involves a thorough review of literally hundreds of systems/subsystems to determine criticality.

At the F-22 EMD decision in 1991, a government and contractor team determined which systems/subsystems would be classified as "safety critical" and "safety significant." The safety definitions on the right side of the above slide were used during this classification. Adequate oxygen supply to the pilot was designated Safety Critical Function 18 (SCF-18). A safety critical function is a function which, if not performed or performed incorrectly, may result in the consequences listed above.

The basic difference between a Safety Critical Item (SCI) and a Safety Significant Item (SSI) is the degree of back-up capability. Failure of a SCI alone may result in unacceptable

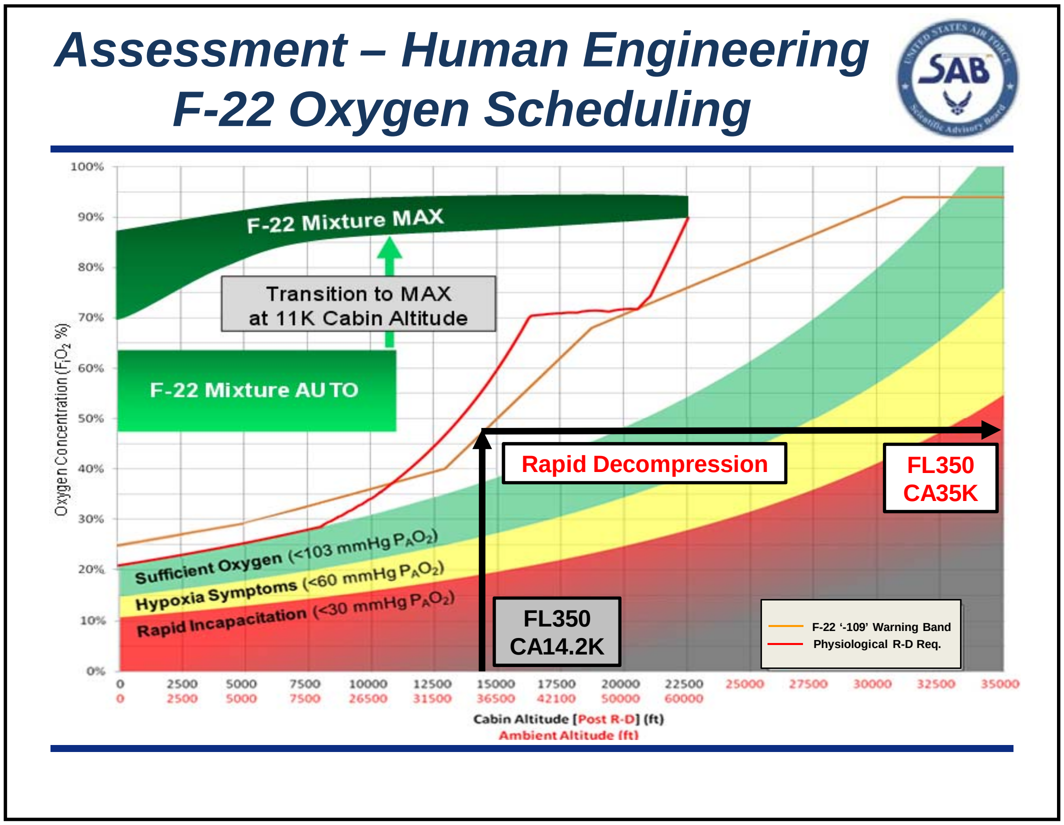
[4] Lockheed Martin Aeronautical Systems Company. "F-22 Post EMD Safety Critical Functions/Safety Significant Items/Safety Critical Items Listing."

consequences. Said another way, SCIs have no back-up. At this time, OBOGS, the BOS, and the EOS were considered “safety significant” because they had back-up capability—each backed up the other. The decision to classify the OBOGS as an SSI had a profound effect on the priority and oversight of the system.




In moving from the fly-off competition into EMD, the F-22 became too heavy to be able to meet some of its Key Performance Parameters. Therefore, the F-22 SPO initiated a comprehensive aircraft weight reduction program. In April 1992, as part of the weight reduction effort, the Life Support System IPT study recommended BOS removal as the EOS was considered an adequate back-up to OBOGS. The AOG Study Panel understands this recommendation was based substantially on the knowledge that the ECS IPT would recommend that an ACM bypass conduit be installed to insure that the OBOGS would always have positive pressure to the inlet valve. However, that bypass conduit was never installed.

The LSS IPT recommendation was implemented via F-22 Air Vehicle Design Directive 033 in early 1992.




### *F-22 Oxygen Scheduling*

The above slide integrates three key aspects of flight physiology and F-22 OBOGS production schedules:

1. Depicted across the "X" axis and moving to the right and up are the oxygen partial pressures and percentages that support three conditions of human performance as the aircraft's and cockpit altitudes increase: Normal (green-shaded region), Hypoxia Symptoms (yellow-shaded region), and Rapid Incapacitation (red-shaded region).
2. Shown half-way up the "Y" axis and continuing up and right is the designed performance of the F-22 OBOGS in terms of the percentage of oxygen required in the Auto Mode or in the Max Mode.
3. The third aspect depicts the safety lines, or level of oxygen that should be produced in order to ensure an acceptable amount of reserve oxygen to provide a crew member adequate time to activate the emergency oxygen equipment before becoming incapacitated. There are two lines depicted: (1) the red line shows the Alveolar Gas Equation which is accepted by the aviation physiology community as the minimum percentage of oxygen in the breathing air at various altitudes; and (2) the orange line is the "Warning Band" that will illuminate the OBOGS ICAWS light should the OBOGS oxygen production percentage not meet the required levels.

Should the F-22 cockpit suffer a rapid loss of cabin pressurization, the required amount of oxygen provided to the pilot at the time of that depressurization should be 55% (as indicated

by the red line at approximately 35,000 feet), but the OBOGS warning band is set for 45% (orange line/vertical black arrow intersection) which is the lowest acceptable number associated with the satisfactory capability of the OBOGS machine.

As depicted in the above slide, such a rapid decompression immediately puts the crew member at risk without an automatic activation of an emergency oxygen supply, even though the OBOGS may be producing enough oxygen to keep the "OBOGS Fail" ICAWS from illuminating. It should be noted that, despite the fact that the F-22 has never experienced a rapid decompression in its operational history, the margin of safety should such an event occur due to combat damage or system failure requires the Air Force to ensure both the "warning band" be adjusted to the alveolar gas equation schedule and the status of the aircraft's oxygen production be known to the pilot.

## Outline

- Introduction
- **Assessments**
  - Engineering
  - **Human Effectiveness**
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The second major area assessed was human effectiveness. This involved the designs of the F-22 ECS/LSS and how well the resultant systems contributed to the effectiveness of the crews operating the F-22. The following areas will be covered:

- Human Systems Integration (HSI) and the F-22 ECS/LSS design.
- Examples of in-flight data collected from ECS shutdowns, G-induced pilot oxygen saturation reductions, and hypoxia incidents (including pulse oximeter data).
- Characterization of chemicals on the F-22 and their potential effects on crew.

***Human Systems Integration, the F-22 Program, and the Design of the F-22 ECS/LSS***

During the early Advanced Tactical Fighter (ATF) development program, the precursor of the F-22 development, HSI analysts were chartered to focus on Manpower, Personnel, Training, and Safety. From 1989 to 1994, analysts from the Aeronautical Systems Division (ASD) HSI Office were collocated to the ATF Program Office. As a consequence of a heightened awareness of the manpower, usability, maintainability, safety, human effectiveness, and cost savings achievable by the application of human factor engineering methods, the analysts and program leadership were able to bring about changes representing different priorities and policies in program management decision-making. Engineering, human factors, manpower, personnel, training, and logistics were integrated.

Technical support of the efforts beyond the HSI technical capabilities embedded within the ATF Program Office came from the Air Force laboratories and the ASD engineering offices

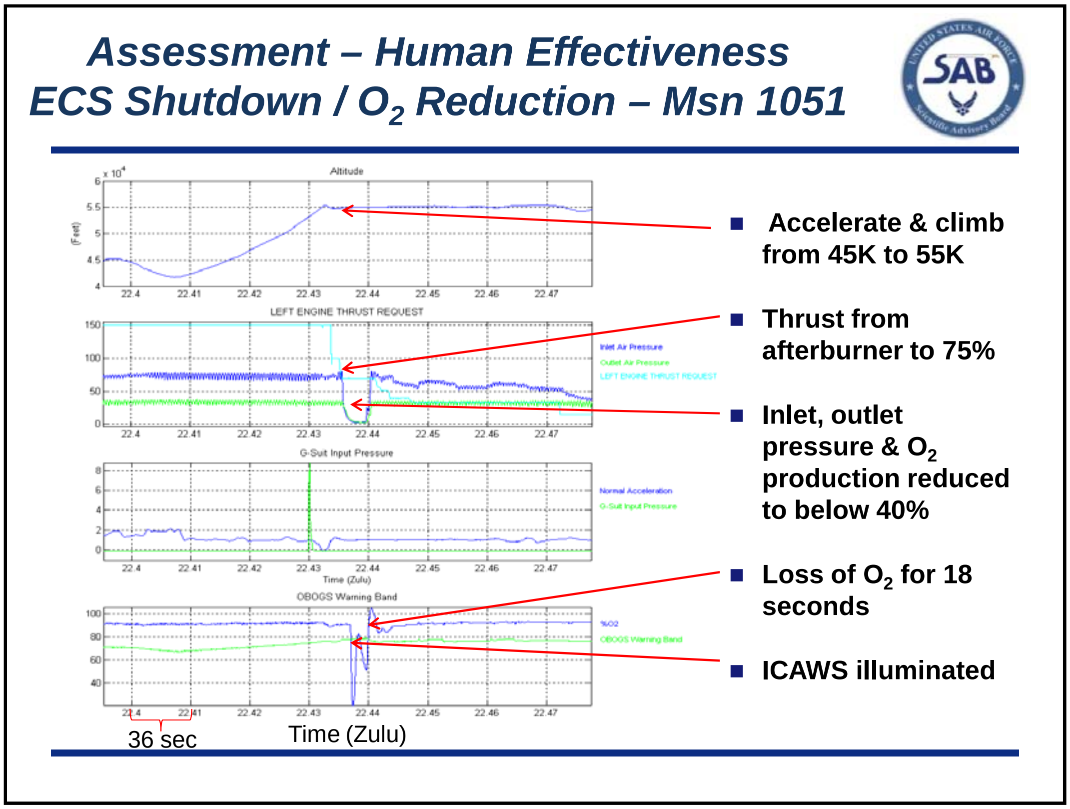
in areas including: crew systems, life support systems, oxygen generation, propulsion, workload management, training methods and simulators, cockpit controls and displays, and human factors engineering. As a result of the ATF contract efforts, the F-22 pilot was given advanced personal protective equipment; integrated sensors, controls and displays; stealth technology; and sustained supersonic cruise.

As the ATF moved beyond the fly-off phase and into the F-22 EMD phase, the acquisition policies had changed, diminishing the influence of proven military standards as well as national and international standards. Additionally, the workforce was downsized in response to acquisition reform initiatives. During the early 1990s, the ASD HSI Office manning was reduced to 21 positions. In 1994, prior to the developmental flight tests of the F-22, the HSI program office was disbanded due to funding and personnel reductions within ASD. The expertise required to perform the critical integration analyses became insufficient.

Further, as a cost savings decision in the 2001 timeframe, the F-22 SPO chose to terminate the contractor developed life support ensemble, in favor of the government developed life support equipment developed as a part of the "Combat Edge" ensemble. In view of the fact that the Combat Edge ensemble had been certified, specialized, end-to-end testing of that equipment for the F-22 was not deemed necessary.

The data depicted in the following charts indicate some anomalies in the performance of the F-22 oxygen and anti-G delivery systems when the ECS system cuts back or shuts down in-flight, or during the onset of High-G forces, which merit further analysis and testing.

Note: The areas of Human Systems Integration (HSI) and the F-22 ECS/LSS design (including the evolution of the USAF HSI enterprise as applied to the F-22 program) are presented in greater detail in Appendix D of this report.




***Example In-Flight Data***

The slide above[5] and the following slide depict representative useful data gathered during the test sorties flown as a result of direction provided by the SIB or suggestions from the AOG Study Panel from April-September 2011. In the above slide, the information collected came from the normal aircraft integrity data, which then informed both the SIB and the AOG Study Panel with regard to sensors to be installed for the dynamic in-flight testing to be done in the summer of 2011.

In the above slide, the upper graph displays aircraft altitude versus time with each time sequence equating to 36 seconds. The second graph depicts the throttle setting (percent, teal line), the inlet pressure at the OBOGS (psi, blue line), and the outlet pressure of the OBOGS (psi, green line). The third graph displays the number of "Gs" being pulled by the aircraft (blue line) and the final graph depicts the percentage of oxygen being produced by the OBOGS (blue line) as well as the oxygen warning band (percent of $O_2$, green line).

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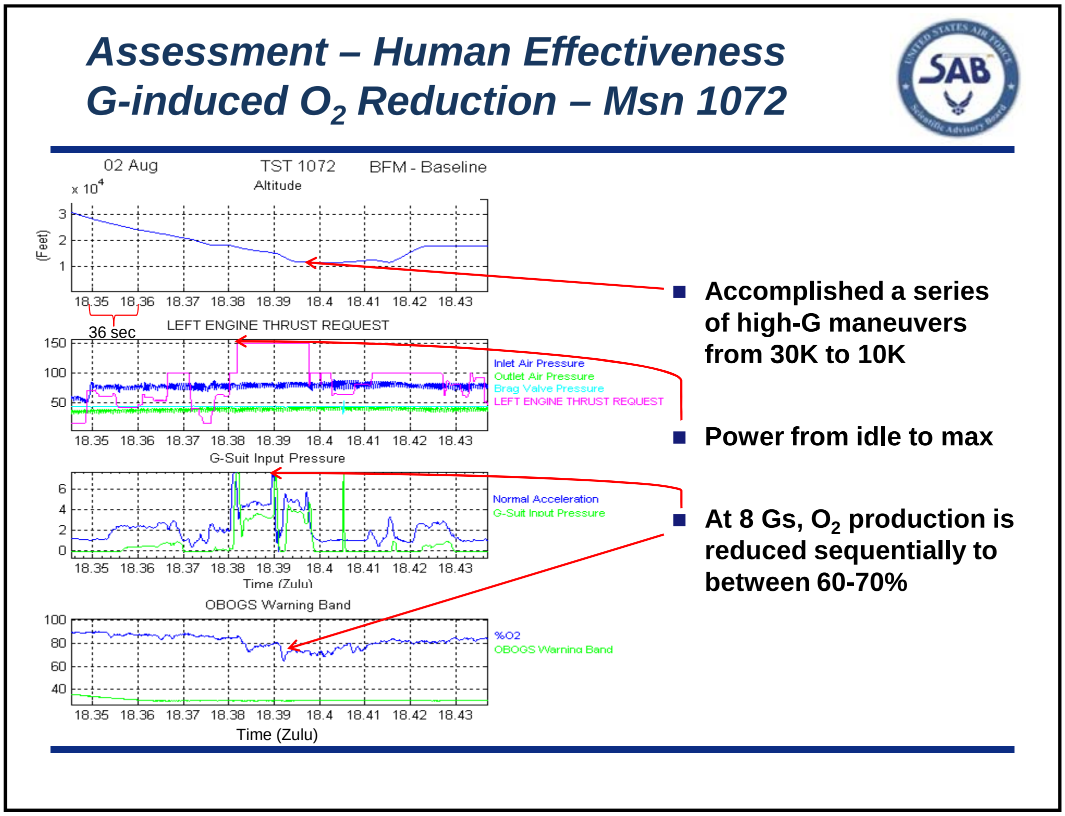
[5] The vertical axis on the second graph is in percent of military thrust requested (teal line) and OBOGS inlet (blue line) and outlet pressure (green line) in psi. The vertical axis on the third graph reflects the number of Gs normal acceleration (blue line) or the G-suit input pressure (green line) in psi. The vertical axis on the last graph depicts the OBOGS output $O_2$ percentage (blue line) as well as the OBOGS $O_2$ percentage warning band (green line).

While the ECS rollback or shutdown at high altitudes and low power settings is an infrequent event, the F-22 SPO is developing a software update that should reduce the number of events in the future.




On the above slide,[6] using the same methodology of Altitude, Power, and OBOGS Inlet and Outlet pressures as on the previous slide, it can be seen that as the aircraft descends and the pilot puts eight Gs on the aircraft (blue line, third graph), the percentage of oxygen (blue line, last graph) produced by the OBOGS is reduced. As the pilot reduces the G load, the OBOGS begins to recover and then the percentage of oxygen produced by the OBOGS is reduced again when the pilot reapplies the Gs.

Note that at the altitudes for this test sortie, the OBOGS $O_2$ percentage warning band (last graph, green line) is quite low and is never breached, even though the amount of oxygen being produced does decrease to between 60% and 70%.

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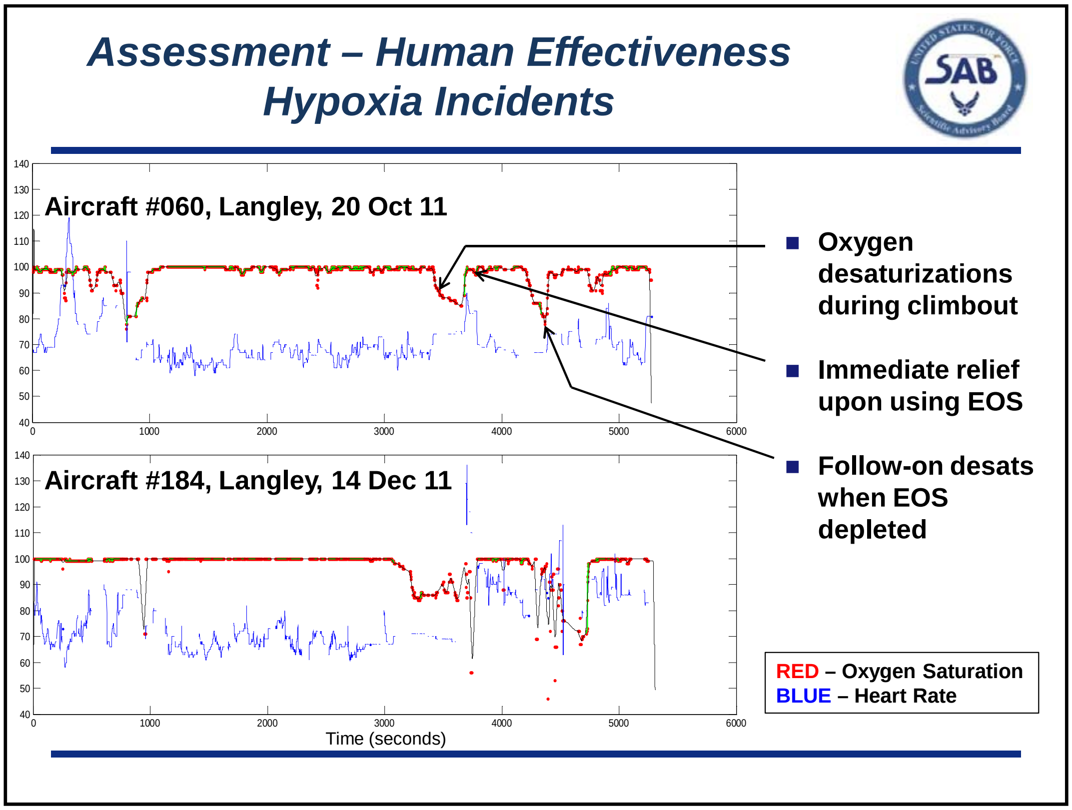
[6] The vertical axis on the second graph is in both percent of military thrust (magenta line) and OBOGS inlet and outlet pressure (blue and green lines) in pounds per square inch (psi), and the BRAG valve pressure (teal) in psi. The vertical axis on the third graph reflects the number of Gs of normal acceleration (blue line) and the G-suit input pressure (green line) in psi. The vertical axis on the last graph depicts the OBOGS output $O_2$ percentage (blue line) as well as the $O_2$ percentage warning band (green line).




The data on the above slide serve to illustrate the utility of the fingertip pulse oximeter during return-to-flight operations. In the first example, the initial measurements are considered an "artifact" or illegitimate reading due to poor contact of the instrument with the fingertip while outside the aircraft. During climb-out, the pilot experiences hypoxia symptoms and observes a lowered oxygen saturation (red line) reading from the pulse oximeter. Upon EOS activation, the oxygen saturation rapidly returns to baseline where it remains until the EOS is depleted. Once oxygen from the EOS is depleted, there is another desaturation that is corrected upon landing and breathing cockpit air. The recording from the second aircraft demonstrates a similar course of events.

A more stable and reliable helmet-mounted pulse oximeter is in development for use in the F-22 (and perhaps other aircraft).

## *Assessment – Human Effectiveness Characterization of Chemicals on the F-22*

**Examples of Chemical Classes Assessed**

- **Alkanes/Alkenes/Alkynes**
- **Alcohols/Aldehydes**
- **Dienes/Esters/Ketones**
- **Organic Sulfur/Phosphorus compounds**
- **Total volatile organic compounds**
- **Other gases (e.g., CO, $CO_2$, $N_2$, Ar)**

**759 Chemicals Assessed***

- **432 could potentially be found in the ECS**
- **208 compounds are potential CNS** toxicants**
- **126 detected to date during aircraft ground and flight testing**
- **Assessment ongoing**

*Molecular Characterization Matrix – Assessment
**CNS – Central Nervous System

**Detected contaminants below published harmful levels, but the role of unmeasured chemicals remains to be determined.**

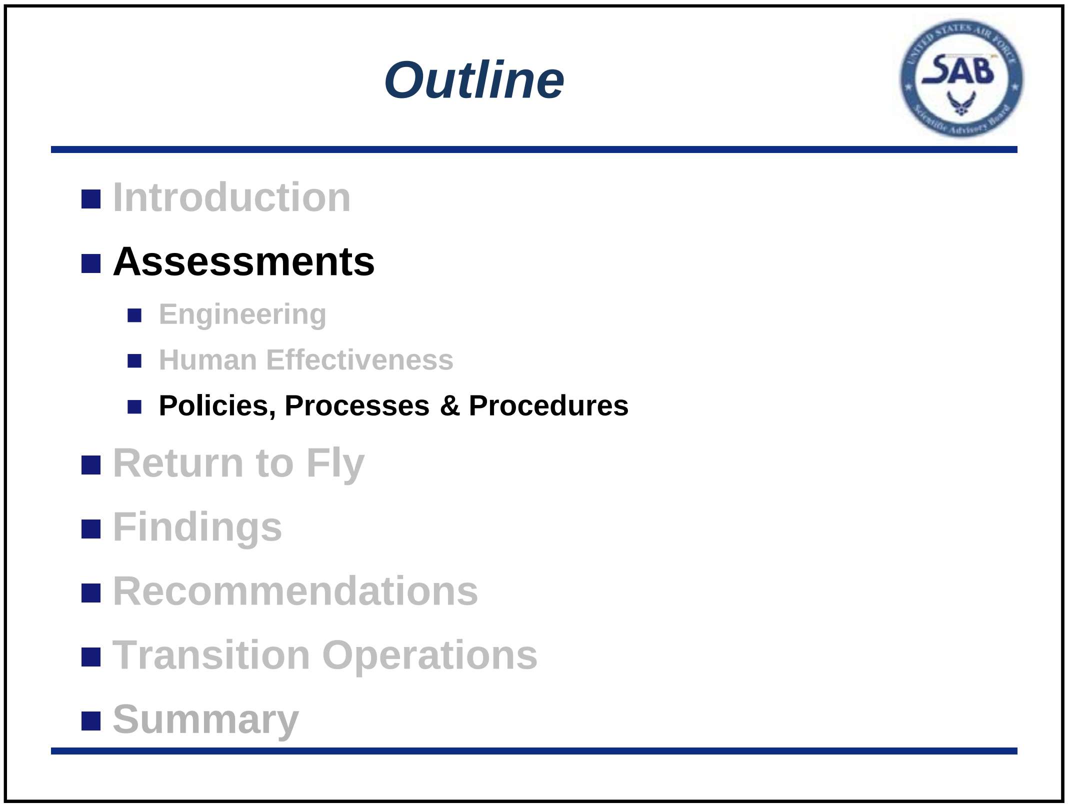
One of the two working hypotheses proposed for this Study addresses the potential for F-22 flight safety being compromised by the presence of toxic levels of contaminants in the air delivered from the OBOGS to the pilot. The presence of high levels of certain classes of chemicals present in jet fuel, jet oil, hydraulic fluid or their pyrolysis products could be a contributing factor in central nervous system (or respiratory) symptoms experienced by pilots and ground crew personnel.

An extensive, multi-step, multi-disciplinary effort was undertaken by personnel from the USAF, Boeing, Lockheed Martin, and other consultants to identify chemicals that might possibly enter a pilot's breathing air on the F-22 and account for acute central nervous system (CNS) effects. The process, termed the Molecular Characterization Matrix (MCM), began with the generation of a list of chemicals known to be present in jet fuel, oil, and hydraulic fluids used on the F-22, together with selected chemicals believed to be associated with the pyrolysis or degeneration of these petroleum products. The focus was on chemicals, gases, or aerosols whose presence in LSS air was considered plausible by virtue of normal operation of the jet engine, or from leaks in seals, valves, or other conduits, or from erosion or out gassing of aircraft coatings. A list of example chemical classes of concern is shown on the chart above. As of January 24, 2012, 759 chemicals associated with the F-22 have been assessed (see Appendix B of this report for an expanded description of this process and specific chemicals characterized).

Based on analysis of available data, the AOG Study Panel concludes that trace levels of volatile organic chemicals are commonly present in the breathing air supplied by the OBOGS used in the F-22. The origin of these contaminants in the breathing air can be traced to their presence in atmospheric air and to leaks of small quantities of jet fuel, oil, or hydraulic fluid into

the ECS of the aircraft. In flight tests and ground tests, neither the level of any single chemical contaminant nor the sum of the concentrations of all the contaminants detected reached a concentration consistent with the CNS symptoms reported in recent incidents. In addition, biological monitoring tests conducted on the blood and urine of incident pilots and ground personnel as well as test pilots were negative for exposure to hazardous levels of carbon monoxide or other toxic substances. The ongoing efforts to identify potential toxicants (MCM activities) in the F-22 and the potential for additive and synergistic toxic mechanisms should continue until all plausible scenarios for chemical toxicity are addressed.

Note: See Appendix B of this report for additional background information on the MCM analysis process and a complete description of the neurotoxicity assessment methodology.




The third major assessment area is an examination of how policies, processes, and procedures affected the development of the F-22 and the OBOGs system. The F-22 acquisition program and the associated decision making was greatly influenced by a series of legislative, reform, organizational, and programmatic actions.

## Assessment – Policies
## The Environment

- **USAF Acquisition workforce reduced 40% between 1992 and 2005**
  - **In implementing Goldwater-Nichols, AF significantly altered its organizational relationships in its systems development structure**
  - **Air Force, with Acquisition Lightning Bolts, transitioned significant development and sustainment activities to major defense contractors**
  - **COTS, NDI, FAR Part 12, TSPR, TSSR, deleted Mil Standards & Mil Specifications**
- **AFMC & AFRL Drawdown**
  - **Reduced Human Effectiveness funding and manpower ~40%**
  - **Moved focus away from aviation physiology, oxygen generation, altitude protection and occupational toxicology specialties**
- **Core competencies and personnel development suffered**
  - **Systems Engineering, Human Systems Integration, Cost Estimating, Safety, Airworthiness, Readiness/Reliability, and Risk Assessment disciplines degraded**
  - **Ability to fulfill "Inherent Government Responsibilities" affected**

The F-22 was developed during a period of substantial change within the Air Force acquisition community. From 1992 to 2005, the USAF acquisition workforce was reduced by 40%. In its implementation of the Goldwater-Nichols Act, the Air Force significantly altered its organizational relationships and systems development structure. For example, the Program Executive Officer structure that was established diminished the authorities of the Air Force Materiel Command (AFMC) and the AFMC Product Centers such as the Aeronautical Systems Center.

In the early 1990s, the Air Force implemented the use of "Acquisition Lightning Bolts," a series of reforms and efficiency initiatives that included transitioning significant development and sustainment activities to major defense contractors. These reforms also contained a number of process efficiency initiatives which included direction to make greater use of commercial off the shelf equipment, non-developmental items, and to take greater advantage of provisions of the Federal Acquisition Regulation Part 12 (e.g., commercial like acquisition, more rapid processes, and fewer rules). Additionally, military standards and military specifications were deleted.

Part of the acquisition workforce drawdown involved a major reorganization of the Air Force Science and Technology (S&T) establishment. On October 1, 1987, the Air Force disestablished the four separate laboratories within AFMC (Phillips Laboratory, Wright Laboratory, Rome Laboratory, and Armstrong Laboratory) and formed the Air Force Research Laboratory (AFRL). The Armstrong Laboratory had been the S&T organization responsible for aviation physiology, oxygen generation, altitude protection, and occupational toxicology specialties. A major rationale for this reorganization was to achieve efficiencies through

consolidation. Funding for the Human Effectiveness Directorate (which had been formed from the Armstrong Laboratory) was reduced by 39.7% and the manning cut by 44% in the Fiscal Year (FY) 1999 and FY 2000 budgets. Additionally, AFRL's Defense Health Program funding (a part of DoD Major Force Program 8) was also withdrawn to become more closely aligned with purely medical applications. AFRL henceforth was funded strictly with S&T funds (Program 6).

In a sense, this created the beginnings of a "perfect storm," wherein these critical areas were reduced from both directions (personnel and funding). It was not so much that the original concept of capturing efficiencies via reorganization was flawed, rather that one of the consequences in execution resulted in a dramatic disinvestment from what heretofore had been critical core mandates for a world class Air Force.

During the course of this Study, the Study Panel conducted numerous interviews with Air Force acquisition personnel regarding the effect of the acquisition workforce drawdown. It was the consensus of these individuals that these reductions had the effect of degrading Air Force capabilities in certain critical disciplines such as systems engineering, human systems integration, safety, air worthiness and reliability, and risk assessment. Moreover, the workload involved in managing today's complex acquisition programs was generally thought to have increased. This reality, combined with fewer professionals to accomplish the increased work, has resulted in less time for personnel professional development (e.g., individual technical and managerial competencies).

One could argue that the net effect of these environmental factors was that the Air Force acquisition community's capability to perform its "inherently government functions" has been negatively affected. It also should be noted that there is no government consensus on what those inherently government functions are.

Note: A more detailed account of the evolution of the Air Force HSI Program (including the effects of funding and personnel changes) is contained in Appendix E of this report.

## Assessment – Policies Process Implications

- Air Force acquisition and sustainment processes related to HSI, safety, and systems engineering changed dramatically
  - Air Breathing Standards are based on 1988 Multi-National and OSHA standards because DOD standards were no longer being maintained
  - Failure Mode Effect and Criticality Analysis last updated in 1980 and rescinded in 1998
  - Determination of Safety Critical Items problematic
  - IPTs were given decision authority unless dealing with significant integration/interdependence issues
  - AF Human Systems Integration plan not fully implemented

In addition to the substantial organizational changes and resource reductions, Air Force acquisition and sustainment processes have also changed dramatically over the past two decades. This is especially true with respect to human systems integration, safety, and systems engineering. For example, as previously mentioned, military standards and military specifications, which in the past had provided clear direction to the contractors, were deleted as part of acquisition reform. Over the years, air breathing standards had been developed as part of a multi-national process, originally by the Air Standardization Coordinating Committee (ASCC), which consisted of representatives from Great Britain, Canada, Australia, New Zealand, and the United States, and later the Air and Space Interoperability Council (ASIC). These standards and guidance documents were supplemented by United States standards, which were later deleted as an efficiency measure.

The multi-national air breathing standards and advisory publications, which guided US aircraft development (including the F-22), were the 1988 ASIC Advisory Publication 61/101/10 and ASCC Publication 61/101/6A. The 1988 Advisory Publication 61/101/10 was recently updated (October 2010) and issued as ASIC Advisory Publication 4060. This update included a substantially more extensive list of contaminants, as well as data on oxygen scheduling for aircraft operating above 50,000 feet. However, it is important to note that these documents constitute only advisory guidance to industry. As of this writing, the Study Panel understands that as a result of this SAB Study and the Safety Investigation Board examination of the F-22 hypoxia-like events and the OBOGS, the Assistant Secretary of the Air Force (Acquisition) has directed that AFMC (via AFRL) develop a comprehensive directive regarding OBOGS that would constitute direction to contractors in the development of Air Force aircraft systems.

While the standard will initially be only directive on the Air Force, it is anticipated that this would become the basis for a DoD directive.

The document which describes the conduct of the Failure Mode Effects and Criticality Analysis (FMECA) process was last updated in 1980 and rescinded in 1994. In examining the use of FMECA in developing the F-22, it is of interest to note that the F-22 OBOGS is a "fly to warn/fail system" and hence periodic inspection and maintenance schedules for the OBOGS were not specified. While the F-22 underwent several criticality analyses, it is not clear that the implications of adopting the fly to warn/fail philosophy were fully considered. (Note: The aircraft will also generate maintenance Fault Reporting Codes when the OBOGS malfunctions. These are recorded on the Data Transfer Cartridge that is downloaded after each flight.)

As discussed earlier in this report, the determination of Safety Critical Items was problematic. The Back-up Oxygen System was deleted in a major weight reduction exercise as the F-22 entering EMD was too heavy to meet requirements. The rationale was that if the OBOGS failed or malfunctioned, the Emergency Oxygen System was believed to be an acceptable back-up. As the EOS at F-22 operating altitudes provides only 5-20 minutes of usable oxygen, it is highly questionable as to whether the EOS was an acceptable back-up.

As modern acquisition programs were becoming increasingly complex and integrated, in the early 1990s the Air Force adopted the concept of Integrated Product Teams to manage the acquisition of systems and subsystems. These IPTs were given broad authority for technical, financial, and contractual decisions, unless the issues in question involved significant integration and interdependence decisions. In those cases, those decisions were handled at a higher level.

Regarding human systems integration, the Air Force efforts to implement an effective HSI program has been characterized by fits and starts over the last three decades. The Air Force first initiated actions in 1985 in response to a 1981 Government Accountability Office report and a Defense Science Board report, which identified a need for centralized control of manpower, personnel, and training (MPT) factors in the acquisition of weapon systems. At this same time, Congress required MPT to be identified at Milestones 1 & 2. (Note: "MPT factors" was the original terminology used to describe what is now known as HSI.)

A prototype organization was established in 1988 at the Aeronautical Systems Center (ASC) to handle the consideration of MPT factors early in the acquisition of major weapon systems. HSI analysts were assigned to support the F-22 systems engineering and development efforts. At that time, the term MPT analyses had been changed to HSI. However, the HSI office staff at ASC was reduced in the early 1990s due to manpower reductions and then disbanded in 1994.

In 1994, the AFMC Director of Requirements approved movement of HSI responsibility to the Human Systems Center (HSC). To make up for what was perceived as a critical HSI shortfall, an HSI cadre was established and initially funded by the Air Force Materiel Command in 1995 to train, advise, and provide consultation to AFMC organizations. The funding and personnel positions were lost in subsequent years, as HSI was never fully embraced into the

acquisition process. In 2004, an Air Force Scientific Advisory Board study[7] recommended that the Air Force adopt proven HSI best practices. The Air Force Surgeon General (AF/SG), recognizing the need and the medical community's role for portions of HSI, restored 31 manpower positions and funding at HSC in 2006. The HSI program was transferred to the Air Force Research Laboratory at Wright-Patterson AFB when the HSC was disestablished in 2008. In 2011, a new HSI Implementation Plan was approved by the AFMC Commander. The AF/SG provided funding for 31 personnel positions with an agreement that this would be a temporary cost share with line funding to be provided in the future. Currently, this plan is not fully funded beyond the Program 8 funding provided by AF/SG and a relatively small amount of Research, Development, Test, and Evaluation funds and Operations and Maintenance funds. The Study Panel understands that additional line funding is expected in FY13 to complete the AFMC HSI Implementation Plan.

Note: As previously mentioned, a more detailed account of the evolution of the Air Force HSI Program (including the effects of funding and personnel changes) is contained in Appendix E of this report.

[7] Erickson, J., & Zacharias, G. "Report on Human-System Integration in Air Force Weapon Systems Development and Acquisition (SAB-TR-04-04)."

## Assessment – Policies
## F-22 Program Implications

- F-22 first major post-Goldwater-Nichols Air Force aircraft acquisition program
- The F-22 was touted as the model for Acquisition Reform
  - Capabilities-Based Requirements
  - Performance-Based Contracting
  - Extensive use of IPTs--decentralized decision making
- Cost caps on EMD and production
- Multiple program restructures
- Significant F-22 Program Office reductions

**Impacts of complex, modern "integrated" system versus legacy "federated" system**

As mentioned, the implementation of these various reforms, organizational, and programmatic actions had far reaching implications for the F-22 and the OBOGS sub-system.

It is important to note that the F-22 was the first major aircraft program in the post Goldwater-Nichols era. The program was considered to be a model for a series of improvements known as Acquisition Reform, as the F-22 SPO adopted much of the philosophy, principles, and processes of this reform initiative.

In the area of requirements, the Air Force adopted capability based requirements which involved changing from performance-oriented specifications (altitude, airspeed, payload) to the capabilities or desired effects orientation. On the contracting side, acquisitions and the resulting contracts were to be structured around results as opposed to stipulating how the work was to be performed.

Because of the size and complexity of the F-22 program, it was realized early on that delegating decision making would be critical. Accordingly, the F-22 SPO enthusiastically adopted the IPT concept and delegated substantial authority for technical, contractual, and financial decisions. It should be noted that the Life Support Systems IPT conducted the study which ultimately recommended that the BOS be removed and a separate Environmental Control System IPT evaluated the merits of installing an ACM by-pass.

The F-22 has been subjected to numerous cost caps on EMD and production. The FY98 the National Defense Authorization Act capped the EMD program at $18.688 billion (B) and production at $43.34B. This program has also seen numerous restructures. There were funding reductions in FYs 1993, 94, 95, and 96. There have also been several production caps at

acquisition milestones as a result of major defense reviews or as part of Program Budget Decisions (PBDs) which progressively reduced the production:

- Milestone I, 750 aircraft
- Milestone II, 648 aircraft
- Bottom-Up Review, 442 aircraft
- Quadrennial Defense Review, 339 aircraft
- Office of the Secretary of Defense PBD 753, 186 aircraft

A diagram which depicts F-22 program key milestones and production caps is included in Appendix F of this report.

As the Air Force acquisition workforce was being reduced, so was the manning in the F-22 System Program Office. In 1992, the SPO was authorized 350 manpower spaces, today the authorization totals 180.

To summarize, the F-22 has been developed during a remarkable period of organizational, process, and programmatic change. These changes are compounded by the basic fact that the F-22 is the first fighter that has been acquired from the start as an integrated system as opposed to a federated or vertical development which had characterized past aircraft acquisitions. This integrated approach introduced an extraordinary system of systems complexities and interoperability challenges, which were compounded by rapid evolution of information technology—these challenges will continue going forward, resulting in significant implications for follow on aircraft development.

# Section 3: Return to Fly

## *Outline*

- Introduction
- Assessments
  - Engineering
  - Human Effectiveness
  - Policy, Processes & Procedures
- **Return to Fly**
- Findings
- Recommendations
- Transition Operations
- Summary

The SAB, in concert with the SIB members and the ACC/SPO Team, was challenged with defining the necessary criteria to return the F-22 to flight status. The following slides provide a discussion of how that process was conducted and the results.

## Flight Operations
## "Return to Fly" Assessment

- "Protect the crews and continue to gather data"
- Establish a "Task Force Team" (led by ACC)
  - Establish the 711th HPW as the data analysis/repository
- Train the crews, maintenance specialists and flight surgeons/aviation physiologists/bio-environmental engineers
- Perform one-time and recurring mx inspections
- Pilots use C2A1 canisters and pulse oximeters
  - Develop an $O_2$ sensor to measure post-BRAG oxygen levels
- Develop and implement post-incident collection protocols for pilots and maintenance specialists
- Operations above 50K MSL authorized

As the AOG Study Panel members reviewed the work done by the F-22 Class E SIB prior to the formation of the SAB Quicklook Study, they assisted in developing the methodology to plan and execute the test sorties. The Study Panel then evaluated the data from those sorties, along with the previous data that had been gathered from the ground functional tests. The process culminated with the AOG Study Panel being able to provide advice to the Air Force so that it could develop a prudent Return-to-Fly program for the F-22 fleet that focused on both protecting the crews and gathering data.

The Return-to-Fly phase was established in such a way that the crews (pilots and maintenance technicians) would be protected and the SIB, the AOG Study Panel, and a newly established ACC-led Task Force would focus on gathering diagnostic data.

Initially, the F-22 Life Support Systems Task Force approached each breathing air anomaly from the perspective of a post-anomaly "functional" investigation. However, over time the Task Force has become more oriented towards a "forensic" investigation with regard to inspection of the F-22's entire life support system.

To date (January 2012), the Return-to-Fly phase has flown about 7,000 sorties. There have been 14 Breathing Air Anomalies, of which six have occurred on the ground during engine runs for maintenance, along with one anomaly that occurred during preparation for a flight. There have been eight anomalies in the air. One was reported by a pilot that experienced a change in the "texture" of the air and one aircraft that had an "OBOGS Fail" ICAWS illuminate on climb out. Neither of these two pilots reported any hypoxia-like symptoms. Two pilots reported fumes, or smoke and fumes, during the flight, and experienced some light headedness or

dizziness symptoms that cleared up with the use of the EOS. Three pilots experienced classic hypoxia-like symptoms in-flight, below 25,000 feet. In each case, they also noted a blood desaturation with their pulse oximeter. In each of those cases, the symptoms resolved quickly when the EOS was activated and the blood saturation level returned to normal. In one case, the symptoms presented after flight and the pilot was treated with the use of the hyperbaric chamber.

As of the date of this report the post flight testing, sampling, inspection, and evaluation protocols have not yet yielded information that could lead to a root cause(s), but two incident aircraft are being outfitted with an expanded set of sensors to be used in a series of follow-on flight test sorties.

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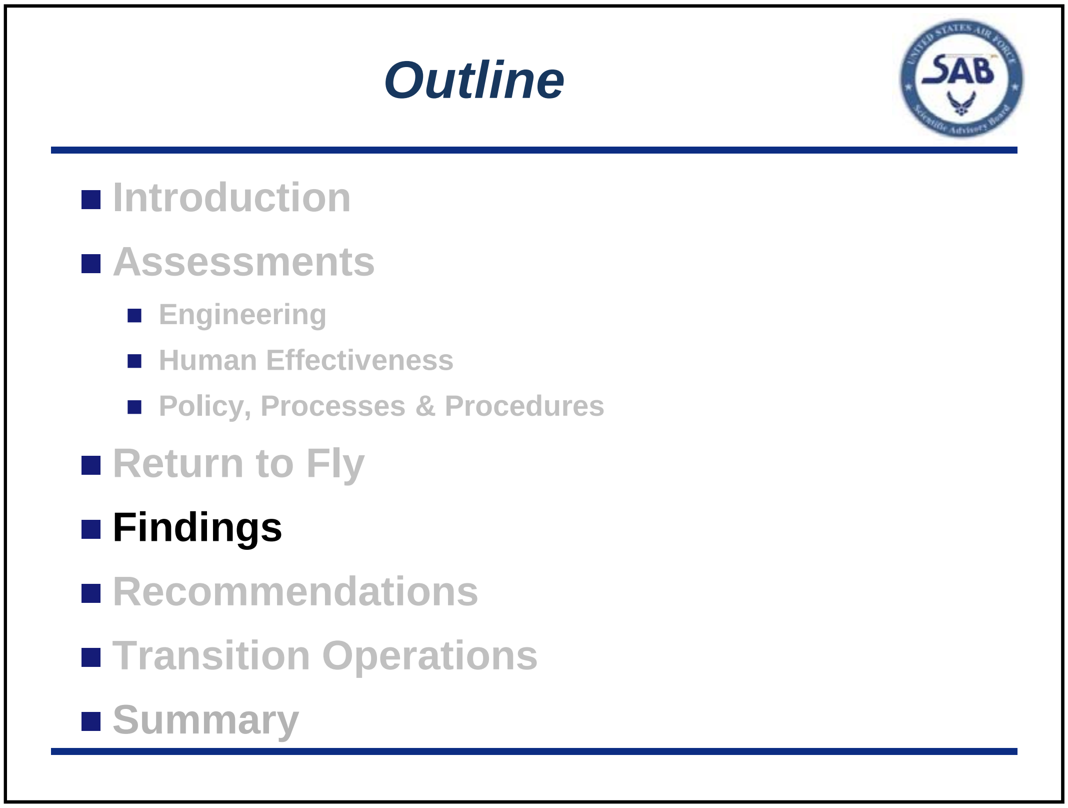
## Section 4:  Findings




The previously described Engineering, Human Effectiveness, and Policy, Processes, Procedures assessments, along with the data collected during the Return-to-Fly activities, led the Study Panel to the following nine Study Findings.  It should be noted, that at the time of the SAB AOG Study Outbrief to the Secretary of the Air Force and Air Force Chief of Staff (January 24, 2012), the root cause(s) has yet to be determined for the F-22 hypoxia-like incidents.  However, the Study Panel believes the actions being implemented protect the crew, significantly robust the system, and will produce additional data likely to lead to identifying the root cause(s).

## *Finding One*

**The F-22 OBOGS, BOS and EOS were not classified as "Safety Critical Items."**

- ***Life Support System IPT eliminated BOS to save weight***
- ***The Environmental Control  System IPT designed an air cycle machine bypass to provide bleed air  to the OBOGS in the event of an ECS shutdown***
- ***The Emergency Oxygen System was deemed to be an adequate Backup Oxygen System***
- ***The Environmental Control System IPT decided to forgo the air cycle machine bypass***
- ***With an ECS shutdown, the pilot's breathing air is cut-off and the pilot is then dependent on either the Emergency Oxygen System or dropping the oxygen mask***
- ***Interrelated and interdependent decisions were made without adequate cross-IPT coordination***

# Finding Two

**Over the past 20 years, the capabilities and expertise of the USAF to perform the critical function of Human Systems Integration (HSI) have become insufficient, leading to:**

- ***The atrophy of policies/standards and research & development expertise with respect to the integrity of the life support system, altitude physiology, and aviation occupational health & safety***
- ***Inadequate research, knowledge and experience for the unique operating environment of the F-22, including routine operations above 50,000 ft***
- ***Limited understanding of the aviation physiology implications of accepting a maximum 93-94% oxygen level instead of the 99+% previously required***
- ***Specified multi-national air standards, but deleted the BOS and did not integrate an automated EOS activation system***
- ***AFMC & AFRL core competencies were diminished due to de-emphasis and reduced workforce to near zero in some domains***

# *Finding Three*

**Modeling, simulation and integrated hardware-in-the-loop testing to support the development of the F-22 life support system and thermal management system were insufficient to provide an "end to end" assessment of the range of conditions likely to be experienced by the F-22.**

- ***Engine-to-mask modeling and simulation was non-existent***
- ***Dynamic response testing across the full range of simulated environments was not performed***
- ***Statistical analysis for analyzing and predicting system performance/risk was not accomplished***
- ***Performance of OBOGS when presented with the full range of contaminants in the ECS air was not evaluated***

# Finding Four

**The F-22 life support system lacks an automatically-activated supply of breathable air.**

- ***ECS shutdowns are more frequent than expected and result in OBOGS shutdown and cessation of breathing air to the pilot***
- ***The F-22 is the only OBOGS-equipped aircraft without either a BOS or a plenum***
- ***The "OBOGS Fail" light on the ICAWS has a 12 second delay for low oxygen, providing inadequate warning***
- ***When coupled with a rapid depressurization at the F-22's operational altitudes, the "Time of Useful Consciousness" can be extremely limited***
- ***The EOS can be difficult to activate, provides inadequate feedback when successfully activated, and has a limited oxygen duration***

## *Finding Five*

**Contaminants identified in the ongoing Molecular Characterization effort have been consistently measured in the breathing air, but at levels far below those known to cause health risks or impaired performance.**

- ***Contaminants that are constituents of ambient air, POL*, and PAO** are found throughout the life support system in ground and flight tests***
- ***OBOGS was designed to be presented with breathable air and not to serve as a filter***
- ***OBOGS can filter some contaminants and there is evidence it may concentrate others***

*** POL - Petroleum, Oils and Lubricants**

**** PAO - Polyalphaolefin**

## *Finding Six*

**The OBOGS was developed as a “fly-to-warn” system with no requirement for initial or periodic end-to-end certification of the breathing air, or periodic maintenance and inspection of key components.**

- ***Engine bleed air certified “breathable” during system development***
- ***OBOGS units are certified at the factory***
- ***No integrated system certification***
- ***No recurring Built-In Test (BIT), inspections or servicing***

## Finding Seven

**Given the F-22's unique operational envelope, there is insufficient feedback to the pilot about the Partial Pressure of Oxygen ($PPO_2$) in the breathing air.**

- ***Single oxygen sensor well upstream of the mask***
- ***12 second delay in activating ICAWS when low** $PPO_2$ **is detected***
- ***Inadequate indication of EOS activation when selected***
- ***No indication of pilot oxygen saturation throughout the F-22 flight envelope***

# Finding Eight

**The F-22 has no mechanism for preventing the loss of the aircraft should a pilot become temporarily impaired due to hypoxia-like symptoms or other incapacitating events.**

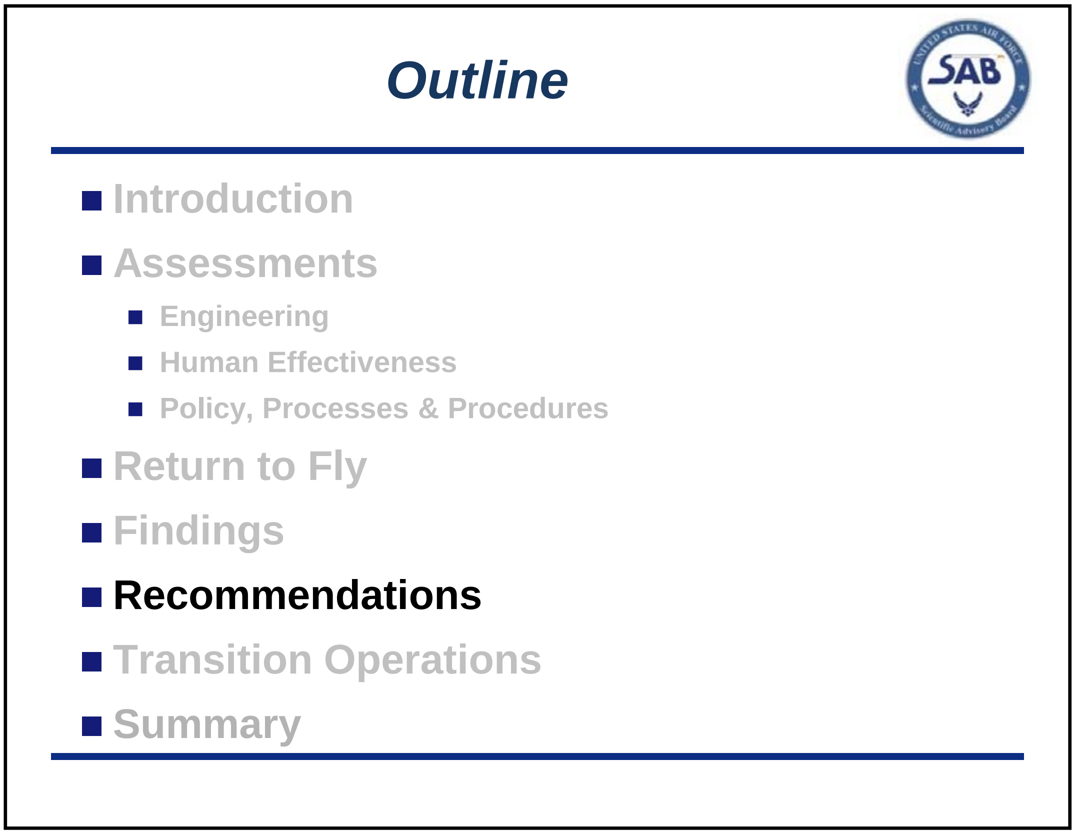
- ***Disorientation, task saturation and/or partial impairment from hypoxia could result in loss of the aircraft and possibly the pilot***

# *Finding Nine*

**The F-22 case study illustrates the importance of identifying, developing, and maintaining critical institutional core competencies.**

- ***Over the last two decades, the Air Force substantially diminished its application of systems engineering and reduced its acquisition core competencies (e.g., engineering, Human Systems Integration (HSI), aviation physiology, cost estimation, contracting, program & configuration management) to comply with directed reductions in the acquisition work force***
- ***By 2009 the Air Force had recognized this challenge and developed a comprehensive Acquisition Improvement Plan (AIP) and a Human Systems Integration plan***
  - ***Although the AIP has been implemented the HSI plan is early in its implementation***
  - ***A clear definition of "inherent government roles and responsibilities" is not apparent***

# Section 5: Recommendations




Based on the previous Findings, the AOG Study Panel makes the following 14 Recommendations to robust the F-22 life sustainment system.

## *Recommendations (1 – 2)*

1. **Develop and install an automatic Backup Oxygen Supply (BOS) in the F-22 life support system.**
   ***(OPR: ACC) (OCR: AFLCMC)***
   - **Consider a 100% oxygen BOS capability unless hazardous levels of contaminants in OBOGS product air can be ruled out**
2. **Re-energize the emphasis on Human Systems Integration throughout a weapon system's lifecycle, with much greater emphasis during Pre-Milestone A and during Engineering and Manufacturing Development phases.**
   ***(OPR: AFMC, SAF/AQ)***
   - **Reestablish the appropriate core competencies*. (OPR: SAF/AQ) (OCR: AFMC, AF/SG)***
   - **Develop the capability to research manned high altitude flight environments and equipment, develop appropriate standards, oversee contractor development and independently certify critical, safety-of-flight elements. *(OPR: AFRL, AFLCMC)***

## *Recommendations (3 – 4)*

3. **Establish a trained medical team with standardized response protocols to assist safety investigators in determining root causes for all unexplained hypoxia-like incidents.** ***(OPR: AFLCMC, AF/SG) (OCR: AFRL)***
4. **Develop and implement a comprehensive Aviation Breathing Air Standard to be used in developing, certifying, fielding and maintaining all aircraft oxygen breathing systems*.*** ***(OPR: SAF/AQ) (OCR: AFMC, AFRL, AFLCMC)***

# *Recommendations (5 – 6)*

5. **Create and validate a modeling and simulation capability to provide end-to-end assessments of life support and thermal management systems. *(OPR: AFMC)***
   - **The initial application should be the F-22 followed by F-35**
6. **Improve the ease of activating the EOS and provide positive indication to the pilot of successful activation. *(OPR: ACC) (OCR: SPO)***

## *Recommendations (7 – 8)*

7. **Complete the molecular characterization to determine contaminants of concern.**
   ***(OPR: AFRL, ACC, SPO)***
   - **Where appropriate alternative materials should be considered to replace potential sources of hazardous contaminants. (OPR: AF/A4/7, AFPA)**
   - **Develop and install appropriate sensor and filter/catalyst protection.**
8. **Develop and implement appropriate inspection and maintenance criteria for the OBOGS and life support system to ensure breathing air standards are maintained.** ***(OPR: ACC) (OCR: SPO)***

## *Recommendations (9 – 11)*

9. **Add a sensor to the life support system, post-BRAG (Breathing Regulator/Anti-G), which senses and records oxygen pressure and provides an effective warning to the pilot.** ***(OPR: ACC) (OCR: SPO)***
10. **Integrate pilot oxygen saturation status into a tiered warning capability with consideration for automatic Backup Oxygen System activation.** ***(OPR: ACC) (OCR: AFMC)***
11. **Develop and install an Automatic Ground Collision Avoidance System (AGCAS) in the F-22.** ***(OPR: ACC) (OCR: SPO)***

## *Recommendations (12 – 14)*

12. **Clearly define the "inherent governmental roles and responsibilities" related to acquisition processes and identify the core competencies necessary to execute those responsibilities.** ***(OPR: SAF/AQ, SAF/FM, SAF/IE, AF/A4/7)***
13. **Create a medical registry of F-22 personnel who are exposed to cabin air or OBOGS product gas and also initiate epidemiological and clinical studies that investigate the clinical features and risk factors of common respiratory complaints associated with the F-22.** ***(OPR: AF/SG)***
14. **Establish a quarterly follow-up to ensure SAB recommendations are implemented in a timely fashion or to respond to any event of significance. The SAB is available for continued support if desired.** ***(OPR: HAF)***

## *Summary*
## *Working Hypothesis Status*

1. ***The F-22 oxygen delivery system is failing to deliver adequate oxygen to the pilot, resulting in hypoxia symptoms that threaten safety of flight***
   - **A. Episodic releases—None documented (Independent $O_2$ sensor will provide additional detection capability)**
   - **B. Low inlet pressure—YES (Mitigated by ECS Software change, improved EOS access and BOS addition)**
   - **C. Failure mode in equipment from OBOGS to mask—YES (Mitigated by recurring inspections and independent $O_2$ sensor)**
   - **D. Leak or failure from bleed air valves to mask—YES (Mitigated by recurring inspections and independent $O_2$ sensor)**
   - **E. OBOGS oxygen delivery schedule and performance—YES, but exceeds physiological requirement (Mitigated by independent $O_2$ sensor)**
   - **F. Change in tier 2/3 supplier/component materials/process—NO**

The above slide and the next give the current status of hypothesis testing as of the final AOG Study briefing given on January 24, 2012.

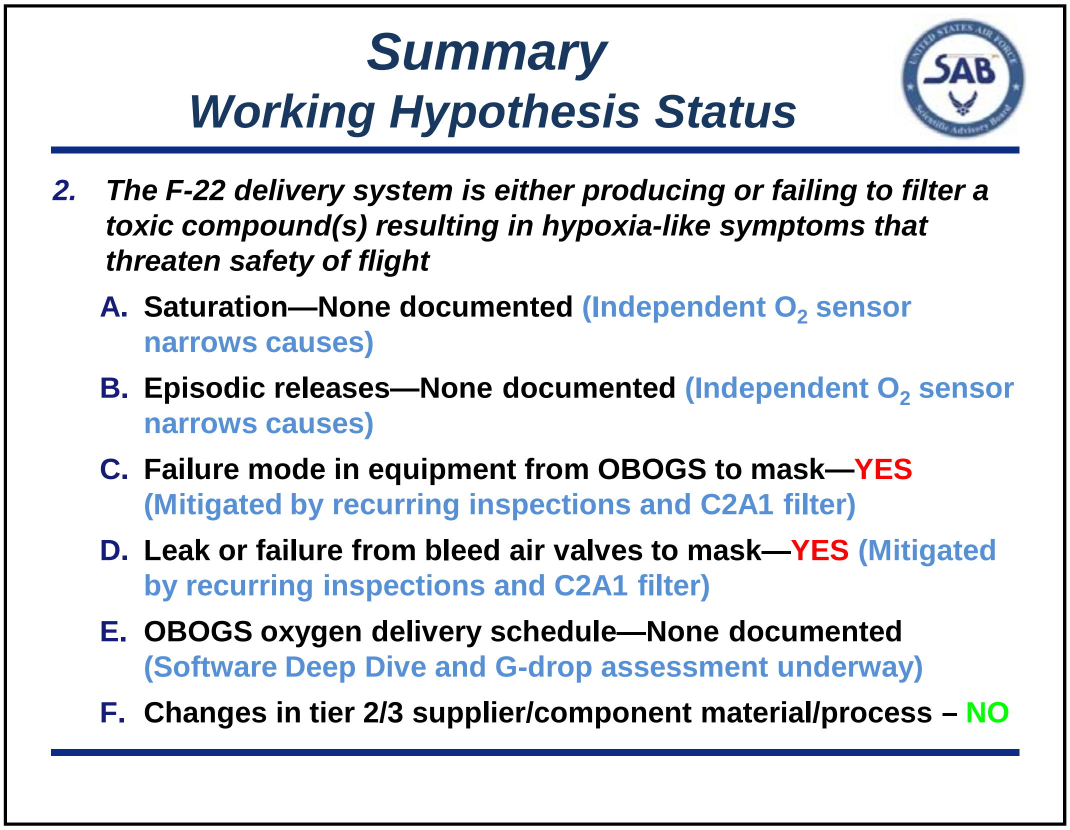
Failure to deliver adequate $O_2$ due to episodic releases of nitrogen was not documented by any of the data flights. However, the Panel was not able to close this hypothesis due to the low number of data flights available. Once additional flights with the additional $O_2$ sensor are flown, this hypothesis should be able to be closed.

Low inlet pressure was documented on several flights with ECS shutdowns, but this failure has been mitigated by improved ECS software minimizing shutdowns, improved access to the EOS, and addition of the BOS.

Leaks or hardware failures in the system were documented; however, these risks were mitigated with improved recurring inspection and installation of the independent $O_2$ sensor which will provide the pilot warning of such a failure.

Failure of the OBOGS to deliver commanded performance was documented with decreases under G-loading; however, in all cases the performance was still above the warning band and above the demands of the pilot as dictated by cabin altitude.

No changes in suppliers or manufacturing processes were documented.




No documented cases of zeolite saturation causing reduced $O_2$ concentration were documented. Installation of the independent $O_2$ sensor close to the pilot's mask will provide warning and additional data on this condition.

No episodic releases of nitrogen or contaminants were documented. The independent $O_2$ sensor will provide warning and additional data.

While hardware equipment failures and leaks were documented, recurring inspections, and the addition of the C2A1 filter mitigate the risk to the pilot while providing additional data on likely contaminant sources.

No anomalies were documented in the oxygen delivery schedule; however, a software deep dive is still underway and a further assessment of the reasons for the drop in $O_2$ concentration noted under G-loads.

No changes in suppliers or component manufacturing processes were identified.

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# Section 6: Transition Operations

## *Outline*

- Introduction
- Assessments
  - Engineering
  - Human Effectiveness
  - Policy, Processes & Procedures
- Return to Fly
- Findings
- Recommendations
- **Transition Operations**
- Summary

As the Air Force continues its Return-to-Fly phase, the AOG Study Panel reviewed the conditions which could permit the F-22 fleet to transition from this rather manpower intensive phase of data collection and analysis to more “normalized” flying operations.

## Transition Operations – Near Term

- Implement improved access to and ease of activation of EOS
- Implement an independent post-BRAG $O_2$ sensor providing indication, warning, and recording capability
- Field helmet-mounted pulse oximeter
- F-22 Life Support Systems Task Force should consider installing CO and $CO_2$ detectors in the F-22 cockpits
- F-22 Life Support Systems Task Force should consider using a vacuum canister during maintenance engine runs and assess the contents should there be an incident
- Leveraging the NASA or similar independent capabilities, develop and implement the appropriate post-incident protocols with greater emphasis on forensic analysis of the entire life support and cabin pressurization systems
- Analyze data gathered to determine effectiveness of the C2A1 filter for safety and data collection
- F-22 Life Support Systems Task Force and 711 HPW identify the need for contaminant mitigation measures for both OBOGS and cockpit breathing air

The above slide depicts the actions that the AOG Study Panel believes should be taken and the steps that should be completed before terminating the F-22 Life Support Systems Task Force phase. Of note are some fairly significant assessments to be made:

First, the F-22 Life Support Systems Task Force should consider if the Air Force should install reliable, relatively inexpensive, carbon monoxide (CO) and/or carbon dioxide ($CO_2$) detectors in the cockpit. It is the Study Panel's view that until contamination of the ECS air can be completely ruled out; detecting the presence of CO and/or $CO_2$ could aid both the pilot and maintenance technician. For the pilot, knowing the quality of the cockpit pressurized air could be very important, especially if activation of the Emergency Oxygen System will not provide enough oxygen to allow the aircraft to reach an appropriate landing base without descending below 10,000 feet. In that scenario, the Air Force may prefer for the pilot to descend to 25,000 feet with a cabin altitude of 10,000 feet or lower, drop the oxygen mask, and breathe cockpit air.

Secondly, for the maintenance technician who may begin to experience hypoxia-like symptoms on the ground while breathing cockpit air, having CO and/or $CO_2$ detectors could provide an immediate indication of the quality of the cockpit air. The F-22 Life Support Systems Task Force should also consider requiring each maintenance technician to employ a vacuum (summa) canister on each ground maintenance engine run. To this point, for each of the engine run anomalies, the Study Panel understands that the F-22 Life Support Systems Task Force has been unable to obtain any data of significance once the maintenance technician has shut down the aircraft, opened the canopy and then had swab tests and summa canisters placed in the cockpit. Having the vacuum canisters present for every engine run should capture the air exactly

at the time of the occurrence. Analysis of the canister air would only be accomplished should there be a hypoxia-like event. Other canisters would be recycled.

The AOG Study Panel was able to establish a relationship with members of NASA's Johnson Space Center who have extensive experience in evaluating and assessing oxygen generation systems. As a result, the Panel believes the F-22 Life Support Systems Task Force may be able to leverage these NASA (or other similar independent capabilities) in further refining their post-incident forensic analysis.

As the data continues to be assessed and analyzed, the F-22 Life Support Systems Task Force should assess the effectiveness of the C2A1 filter for both safety and data collection. They should also bring to closure the Molecular Characterization effort to determine the need for developing contaminant mitigation measures.

## *Transition Operations – Long Term*

- **Install an automatically-activated Backup Oxygen System (BOS)**
- **Determine, through further data analysis, the need for aircraft mounted measurement and mitigation of contaminants in the breathing air**
- **Develop and install an AGCAS for the F-22**

Although more normalized operations can be achieved with the steps discussed on the previous slide, there are some follow-on permanent steps (install automatic BOS and Automatic Ground Collision Avoidance System (AGCAS), determine need for aircraft mounted measurement/mitigation of breathing air contaminants), that should be taken to provide the F-22 with a more robust life support system capability to ensure mission effectiveness.

## Summary

- Since 2008, the F-22 fleet has experienced an unacceptable number of unexplainable hypoxia-like events
- The Air Force Scientific Advisory Board and the F-22 Life Support Systems Task Force have not yet determined the root cause(s) of the incidents, but have identified and mitigated a number of risks
- The measures taken to protect the crews and gathering of appropriate data are providing substantive and valuable information and have narrowed the possibilities while maintaining combat capability
- Continuing the aggressive Task Force approach with all ECS/OBOGS anomalies will be critical in resolving the unexplained hypoxia-like events
- Implementing the Findings and Recommendations along with the considerations presented in the Transition Operations section should provide the F-22 with a significantly improved margin of safety and operational effectiveness

Implementing the Recommendations and the considerations presented in the Transition Operations section of this report will provide the F-22 with a significantly improved margin of safety and operational effectiveness.

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# Appendix A: United States Air Force and Navy Aircraft Oxygen Generation (AOG) Systems

This appendix describes the AOG systems found on most other Air Force and Navy aircraft. These systems are highly common in basic technology, but also exhibit several unique differences in design philosophy and implementation. At the end of the description for each weapon system, the recent history of hypoxia-like incidents is identified with emphasis on the unknown cause incidents where no root cause is documented.

## A.1 F-15A-D Eagle

*Figure A-1. F-15A-D Legacy Liquid Oxygen (LOX) Converter.*

The F-15A-D has retained the traditional liquid oxygen (LOX) system. This system (Figure A-1 above) uses ground-serviced LOX (99.99% pure), which is converted to a gas before it is delivered to the aircrew. The system then makes use of a dilution regulator in the cockpit to mix the gaseous oxygen ($O_2$) with cockpit air to achieve the appropriate partial pressure of oxygen for the cabin altitude. The crew has the option of selecting 100% where the breathing

gas is 100% oxygen. These systems have been in use for many years, and while they have the advantage of being able to provide 100% $O_2$, they require extensive ground servicing and LOX production capability with the associated logistical footprint. A separate emergency oxygen system (EOS) is seat-mounted and can be manually activated or activated by ejecting. The unit size is approximately 20 x 16 x 18 inches (in).

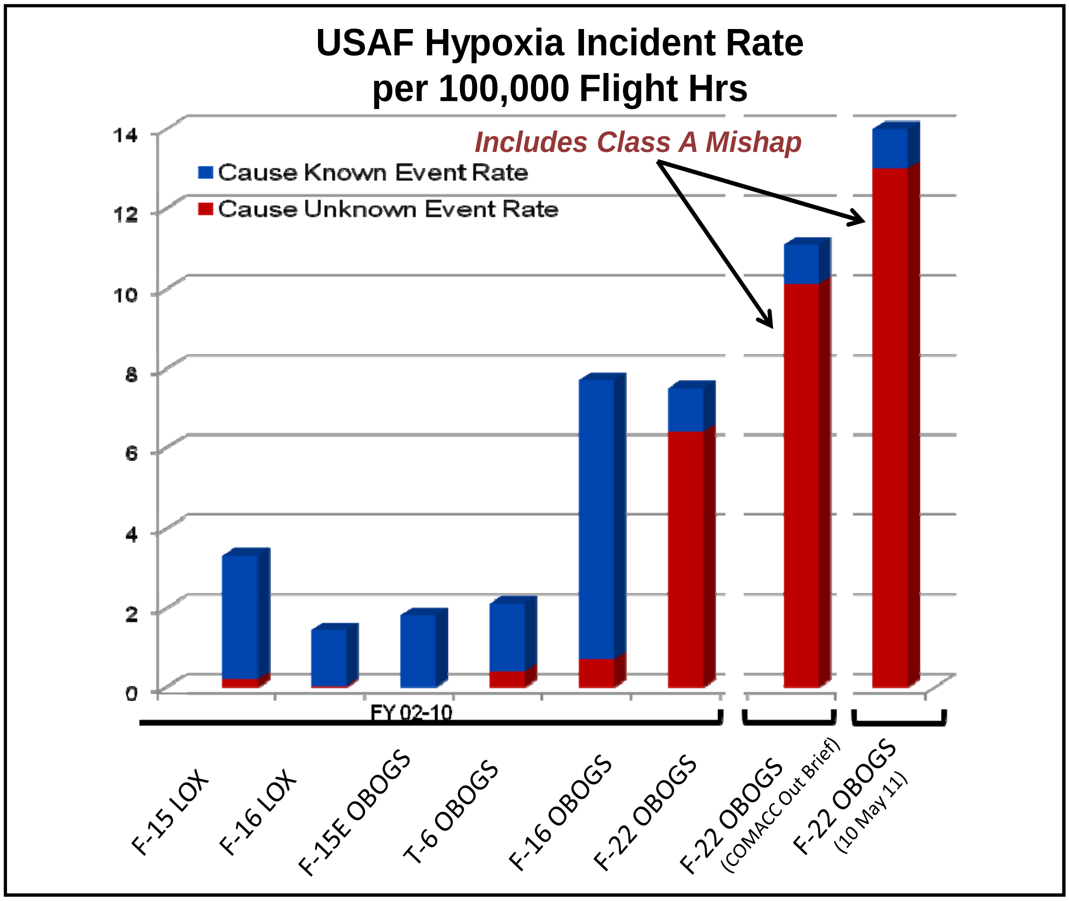


*Figure A-2. USAF Hypoxia Rates for Selected Aircraft.*

As noted in Figure A-2 above, F-15A-D aircraft have had a low rate of hypoxia incidents and a very low rate of unknown cause incidents where root cause could not be identified. Most incidents were attributed to a mechanical system failure, hose routing, or contaminated LOX.

## A.2 F-16 Fighting Falcon (Unmodified Pre-Block 50) and F-18A/B Hornet

F-16 aircraft delivered prior to 1997 were delivered with a LOX system similar to that used on the F-15A-D aircraft. Many of these aircraft were later retrofitted with the On-Board Oxygen Generation System (OBOGS) which were delivered on the new Block 50 aircraft.

As noted for the F-15A-D, the early F-16 aircraft had a very low rate of hypoxia incidents and no recent unknown cause incidents. Most incidents were caused by improper routing of hoses which then became restricted in flight.

## A.3 F-15E Strike Eagle

The F-15E Molecular Sieve Oxygen Generation System (MSOGS), OC1093 Oxygen Concentrator (Figure A-3 below), supplies oxygen for crew members with the added benefit of supporting Pressure Breathing for Gs (PBG) regulators. The unit incorporates a rapid-cycle pressure-swing adsorption process, which uses two molecular sieve filled beds to generate oxygen enriched breathing gas on board the aircraft. These beds are packed with 13X zeolite held in place by positive spring pressure. The system has a 0.01 micron coalescing input filter designed to capture aerosols and water and a 0.1 micron output filter to retain zeolite particles. The unit size is approximately 13 x 12 x 18 inches.

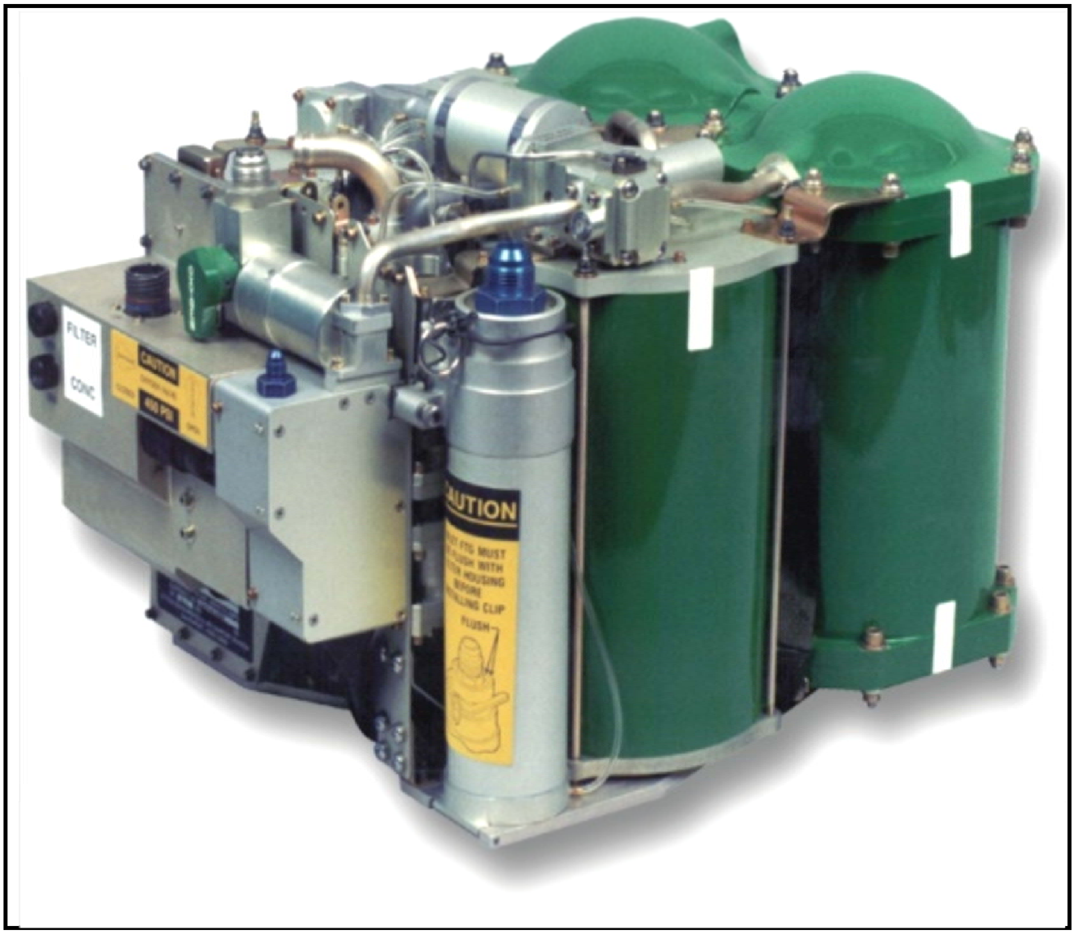


*Figure A-3. F-15E Molecular Sieve Oxygen Generation System.*

This system also contains an integral oxygen monitor, self-test features, and a single-stage air-driven booster pump which charges a built-in, automatically activated back-up oxygen supply (BOS) with product gas. The MSOGS always operates at maximum efficiency producing about 93% oxygen which is then diluted by cockpit-mounted regulators. These CRU-98 regulators are similar to the CRU-73A regulators used in F-15A-D aircraft, except they have been modified to provide positive pressure breathing as a function of G-forces. Also, the CRU-98 is tuned to allow a slightly richer mix of the MSOGS gas with cabin because the MSOGS makes 93% $O_2$ and the older LOX system provided virtually 100% oxygen. The system

has a mean time between failures (MTBF) of 2,000 hours, requires replacement of the inlet filter every 400 hours, and it incorporates a Built-in-Test feature.

The F-15E has a very low hypoxia incident rate with almost no unknown cause incidents. Two unknown cause incidents occurred on the same aircraft. The problem was eliminated when the unit replaced the left engine on the recommendation of the Depot. No root cause was ever determined.

## A.4 F-16 Block 50, Retrofitted F-16 Aircraft

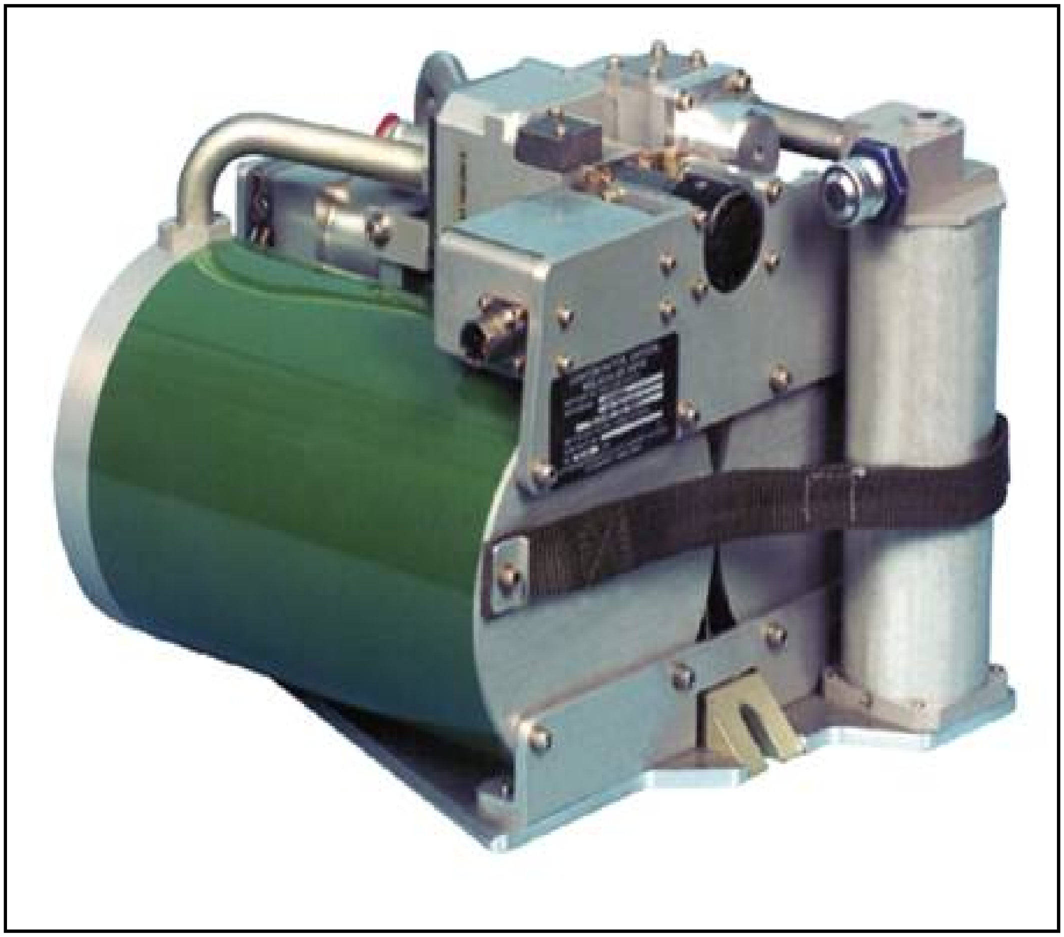

*Figure A-4. F-16 Block 50 OBOGS.*

The OBOGS system used on F-16 Block 50 aircraft (Figure A-4 above), and being retrofitted to earlier blocks, is very similar to the system on the F-15E. The unit incorporates a rapid-cycle pressure-swing adsorption process, which uses two molecular sieve filled beds to generate oxygen enriched breathing gas on board the aircraft. These beds are packed with 13X zeolite held in place by positive spring pressure. The system has a 0.01 micron coalescing input filter designed to capture aerosols and water and a 0.1 micron output filter to retain zeolite particles. Unlike the F-15E, the F-16 makes use of a 250 cubic inch plenum rather than the BOS on the F-15E. This plenum provides 5-6 minutes of breathing air with a system shut-down. The unit size is approximately 12 x 9 x 13 inches.

As noted in Figure A-2 (previous), the F-16 OBOGS system has had a higher rate of hypoxia incidents. The leading cause of those incidents where root cause was identified was hose routing, while two of the three unknown cause incidents were attributed to symptoms consistent with hyperventilation.

## A.5 F-18C/D/E/F/G Hornet/Growler


*Figure A-5. F-18 Oxygen Concentrator System. Note: The Oxygen Concentrator is Used on New Production F-18C/D/E/F/G aircraft.*

The F-18C/D/E/F/G aircraft make use of the OC1169 Oxygen Concentrator system (Figure A-5 above). This is twin sieve system similar in operation to the F-15E system. The two zeolite cylinders contain 5AMG zeolite in a packed configuration. The inlet filter is the 0.01 micron coalescing design with the outlet filter being a 0.6 micron to protect against zeolite particle movement into the gas product. The system includes a 97 cubic inch plenum. The unit size is approximately 14 x 9 x 13 inches.

The F-18 has experienced a significant number of hypoxia-like events over the past few years. The US Navy investigation of these events has attributed the majority to the pilot's breathing elevated levels of carbon monoxide (CO) on the carrier deck. The Navy is adding a catalyst filter to eliminate CO in the product gas.

## A.6 AV-8B Harrier II


*Figure A-6. AV-8B Oxygen Concentrator.*

The AV-8B currently uses the OC1172 Oxygen Concentrator (Figure A-6, above). Its functioning is similar to that of the unit installed in the F-15E. It uses two packed 5AMG zeolite beds with the 0.01 micron coalescing inlet filter and the 0.1 micron outlet filter. The system also provides a 73 cubic inch plenum. The unit size is approximately 13 x 11 x 11 inches.

There were no reported hypoxia-like incidents with the AV-8B.

## A.7 T-6A Texan II

The OBOGS on the T-6A consists of the OC1132 Oxygen Concentrator (Figure A-7 below). This concentrator consists of two beds of packed 13X zeolite with a 0.01 micron inlet filter and a 0.1 micron outlet filter on the zeolite beds. Its functioning is similar to that on the F-15E with the exception that its plenum is sized at 300 cubic inches (in). The unit size is approximately 13 x 9 x 10 inches.


*Figure A-7. T-6A Texan II Oxygen Concentrator.*

The T-6A has had a low rate of reported hypoxia incidents. Early system reliability was degraded to 967 hours MTBF due to problems with a faulty slide valve and a pressure reducer. Recent reliability is much improved. No unknown cause incidents have been reported.

## A.8 B-1B Lancer

The B-1B uses conditioned bleed air to drive six canisters filled with immobilized 13X zeolite. The zeolite crystals are immobilized by binding with an organic polymer. These canisters have both inlet and outlet filters that consist of borosilicate glass fibers bonded with epoxy resin. The element is replaceable and removes contaminant particles from incoming bleed air and the breathing gas to a level of 0.6 microns.

The oxygen system (Figure A-8 below) provides oxygen enriched gas of sufficient pressure to maintain crew breathing requirements at all times. Breathing gas (93% $O_2$) is provided from the primary sub-subsystem, and 100% $O_2$ from the back-up and emergency sub-subsystems. The back-up sub-subsystem is an alternate source of 100 percent oxygen for the flight crew and is ground serviced by maintenance. The unit size is approximately 16 x 24 x 18 inches.

The B-1B has a very low reported rate of hypoxia incidents and no reported unknown cause incidents.

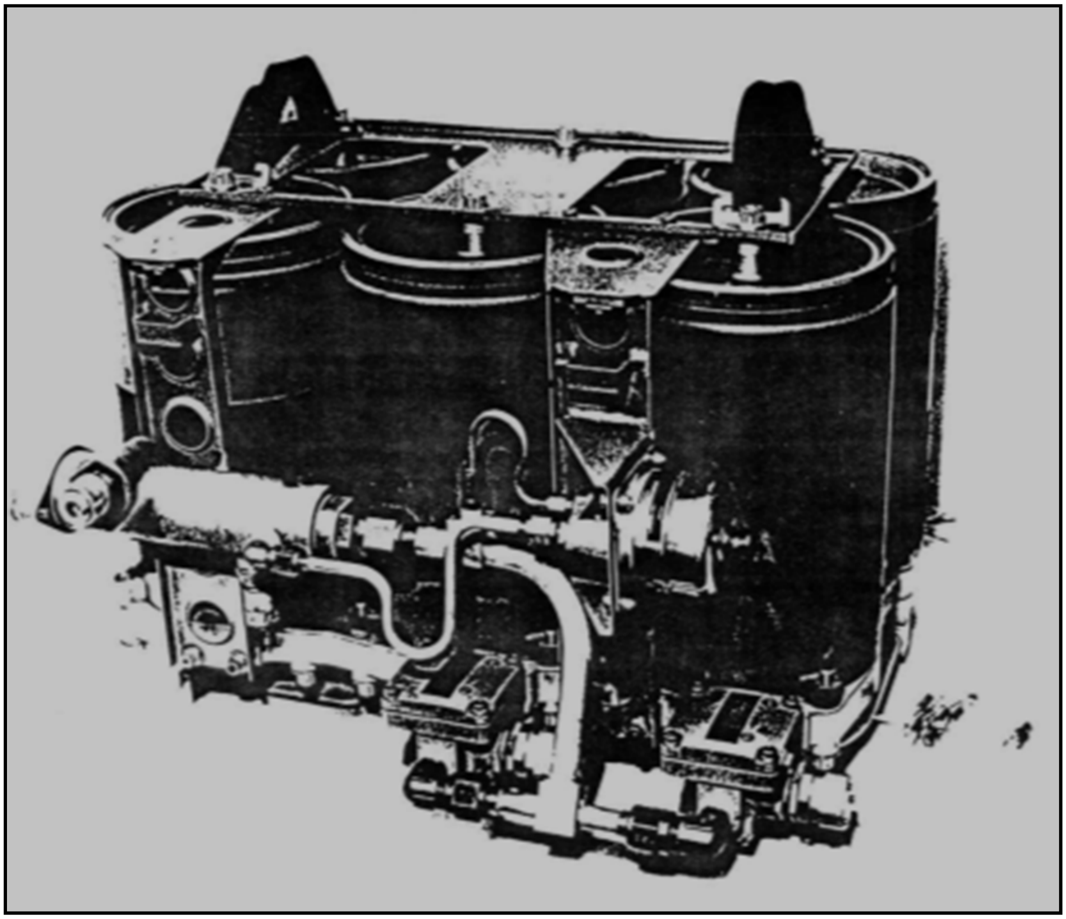

*Figure A-8. B-1B Lancer Molecular Sieve Oxygen Generation System.*

## A.9 B-2A Spirit

The B-2A Oxygen Generation and Distribution System (Figure A-9 below) uses conditioned bleed air to drive three canisters filled with immobilized 13X zeolite. The zeolite crystals are immobilized by binding with an organic polymer. These canisters have both inlet and outlet filters that consist of borosilicate glass fibers bonded with epoxy resin. The element is replaceable and removes contaminant particles from incoming bleed air and the breathing gas to a level of 0.6 microns. The unit size is approximately 18 x 15 x 13 inches.

The B-2A has a very low reported rate of hypoxia incidents and no reported unknown cause incidents.

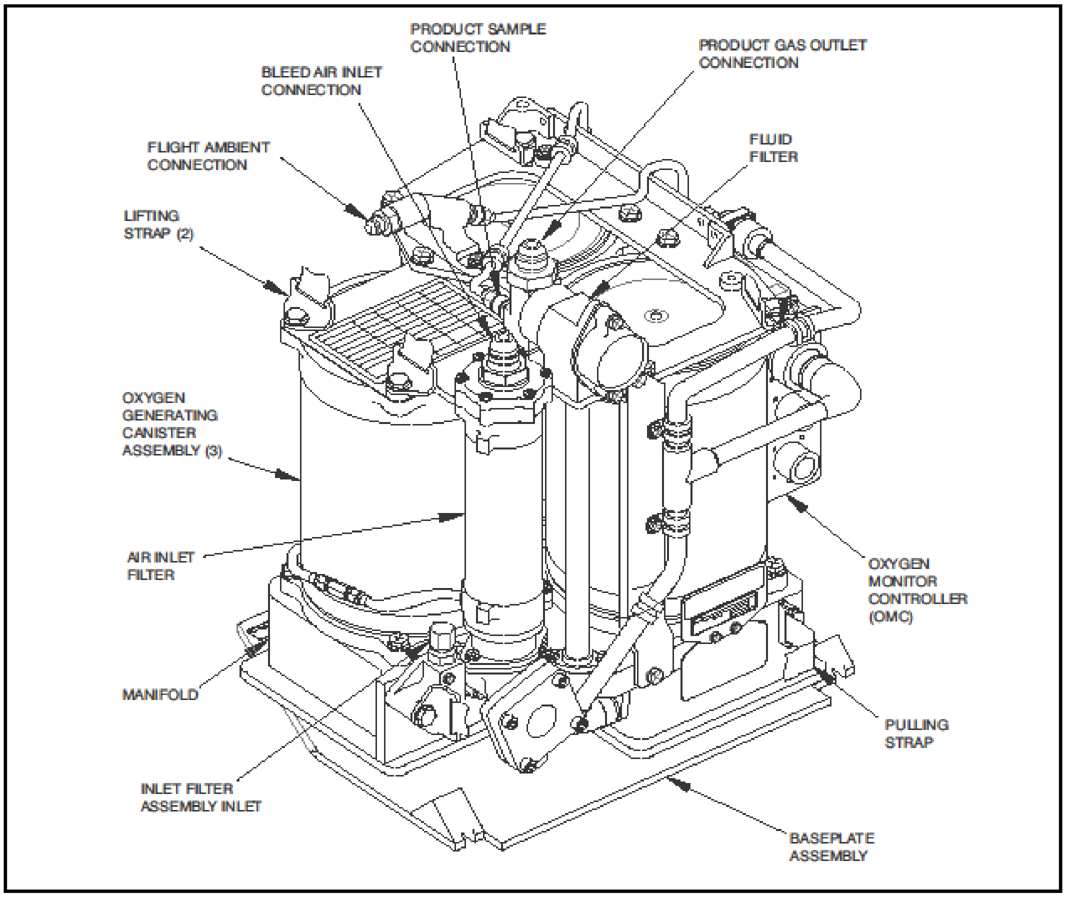


*Figure A-9. B-2A Spirit Oxygen Generation and Distribution System.*

## A.10 V-22 Osprey

The OC1129 oxygen/nitrogen concentrator (Figure A-10 below) performs the functions of two separate systems. First, it supplies oxygen-enriched air for aircrew breathing and second, it supplies inert gas to the fuel tanks to protect the aircraft from fuel tank explosion and fire. The system uses four canisters of zeolite and an integrated plenum. The unit size is approximately 16 x 11 x 25 inches.

There have been no reported hypoxia incidents in the V-22 series aircraft.

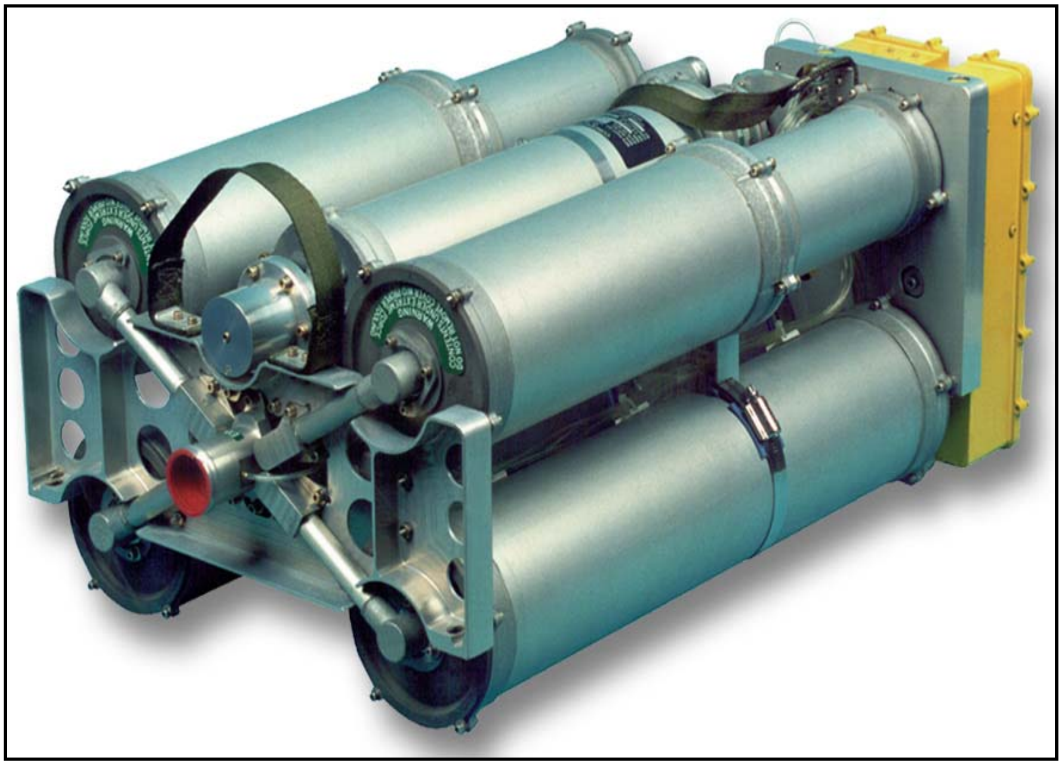

*Figure A-10. V-22 Osprey Oxygen/Nitrogen Generation System.*

## A.11 F-35 Lightning II

The F-35 OBOGS (Figure A-11 below) uses two immobilized 13X zeolite beds to generate the oxygen enriched breathing gas. Like the F-22 system, the F-35 controls dilution as a function of cabin altitude by controlling the charge-purge cycle times of the molecular sieve canisters. Both inlet and outlet filters protect against 0.6 micron particles. A seat-mounted BOS provides automatic fill-in to complement OBOGS during flight transient conditions and is automatically selected during ejection. This BOS obviates the need for a separate EOS. The unit size is approximately 16 x 15 x 5 inches.

The F-35B has had a single hypoxia-like incident. In that incident the pilot had spent 25 minutes breathing the exhaust (CO) of the chase aircraft sitting on the ground before takeoff.

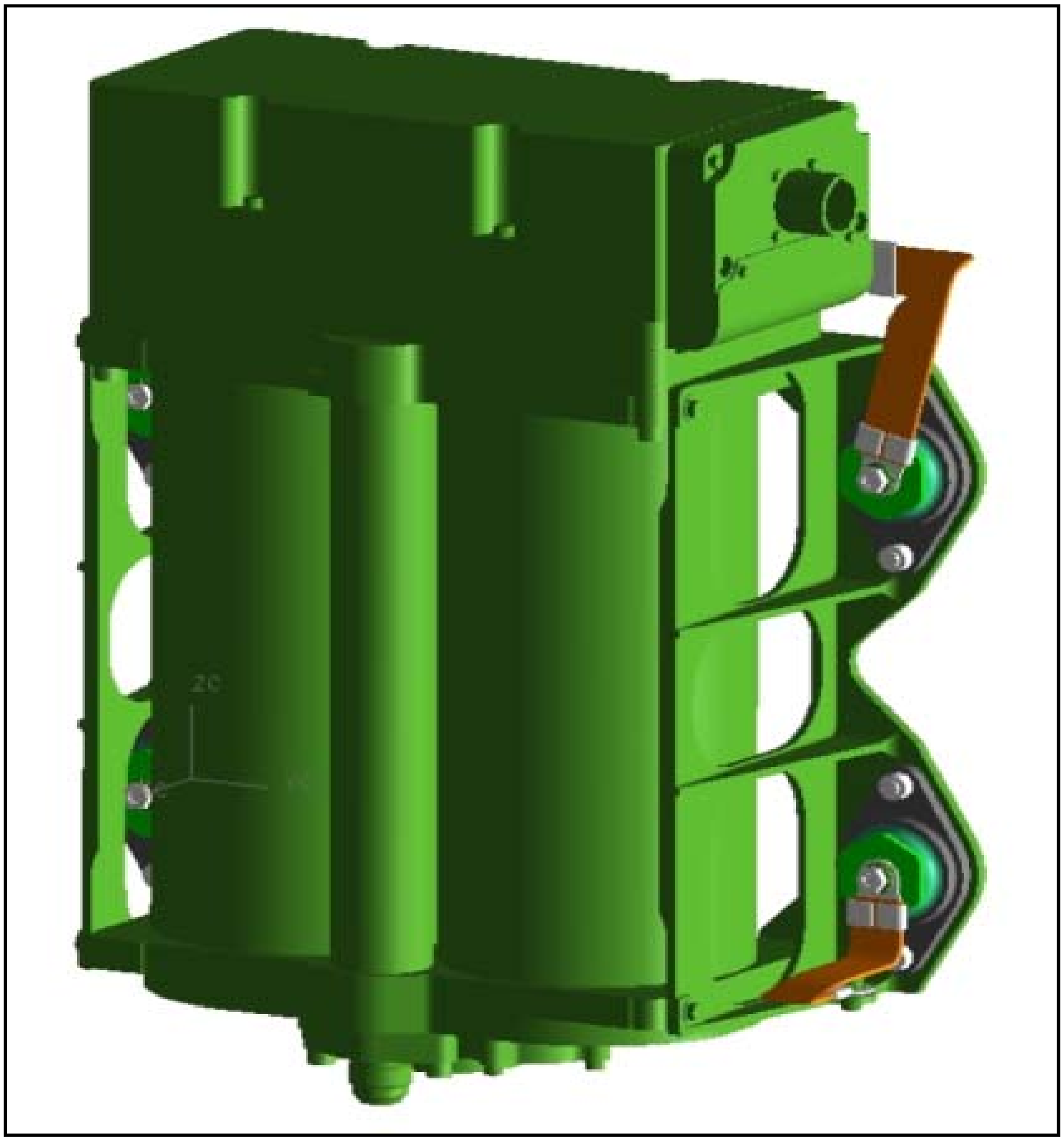

*Figure A-11. F-35 On-Board Oxygen Generating System.*

## A.12 Summary

Table A-1 (following) provides a summary of the various current USAF and USN OBOGS installed in their aircraft. All of these weapon systems, which leverage the OBOGS technology, have certain common traits:

- They all use conditioned bleed air from the engine as the breathing gas. Conditioning varies by mission design series. While all use heat exchangers, the cooling fluid might be air or fuel or polyalphaolefin.
- None of the systems use a catalyst or filter to explicitly filter potential contaminants in the bleed air; rather, they assume the bleed air is "breathable." (The F-18 is moving towards a catalyst to eliminate CO in the breathing air).

- All depend on Pressure Swing Adsorption process to generate enriched oxygen from ambient air using the ability of adsorbents (synthetic zeolitic molecular sieve) to absorb primarily nitrogen.
- All systems have a Built-in-Test Feature and use a Zirconia Oxygen Sensor.

The systems, however, have some differences in implementation:

- Some of the canisters of zeolite are loosely "packed" and held in place by mechanical forces while some immobilize the zeolite in a clay or an organic polymer.
- All of the systems, except for the F-22 implementation, include a Backup Oxygen System or a Plenum (reservoir) to provide some period of enriched oxygen with a shutdown of the OBOGS.
- Input filters vary from an input filter that is 93% efficient at 0.01 micron to one that is designed to filter at the 0.6 micron level.
- Two different types of zeolite are used. The Air Force uses a 13X zeolite while the USN uses a 5AMG zeolite.
- Outlet filters range from 0.1 micron to 0.6 micron to 30 microns on the V-22.
- With the exception of the F-22 system, all have scheduled filter replacement at about 400 hours of operation. Several also have routine replacement of the zeolite material.

## A.13 Finding and Recommendation

**Finding:** With the exception of the F-22 OBOGS, AOG systems have a proven history of safe, repeatable performance with robust back-up in BOS or Plenum systems.

**Recommendation:** Remain wary of a rise in the rate of unknown cause hypoxia incidents and monitor filter status for contaminants.

| | Input Filter (particle)? | Zeolite | Immobilized vs Packed | Check Valve | Plenum/ Storage Tank | O2 % Produced | OBOGS Mounted Monitor | Ckpt Mounted Regulator | Output Filter (particle)? | O2 Dilution | CRU 94 | CRU 120 | CRU 122 | EOS Feedback to pilot | Sche'd Mx | BIT | Oxygen Sensor (type & where?) | Pressure Sensor (type & where?) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F-15E | 93% Efficient at .01 micron | 13X (2 beds) OXY-SIV 5 | Packed | Sieve bed outlet | No Aircraft plenum; self replenishing 450 psig BOS (262 liter NTPD) | 94% @ 26.7 lpm, 90% @ 35 lpm, 34% @ 100 lpm | Yes | Yes (CRU-98) | 99.99% efficient @ .1 micron | Yes | Yes | No | No | Automatic activation of BOS, Master Caution, Oxygen Warning Light, BOS pressure displayed on CRU-98. None for seat mounted EOS. | Inlet filter element change 400 hour phase | Power-up BIT every start up | Zirconia oxygen sensor in monitor concentrator | Cabin pressure sensor for calculation of PPO2 in concentrator based monitor, Outlet pressure sensor automatically switching to BOS between 14 and 22 psig outlet pressure. |
| F-16 | 93% Efficient at .01 micron | 13X(2 beds) OXY-SIV 5 | Packed | Sieve bed outlet | (1 ea) 250 cu/in plenum single seat; (1 ea) 250 cu/in plenum & (1 ea) 100 cu/in plenum two seat. | 93% @ 26.7 lpm, 34% @ 100 lpm | No | Yes (CRU-98) | .4 to .6 micron | Yes | No | Yes | No | REOS manually activated. Feedback in the form of safety pressure breathing and REOS pressure gauge | Inlet filter element change at 400 hours | EBIT part of preflight, MBIT every 400 hours with the filter change or during fault isolation resulting from an Oxy-Low indication | Zirconia oxygen sensor in panel mounted monitor | Cabin pressure sensor for calculation of PPO2 in panel mounted monitor, Product pressure sensed by airframe pressure switch set at 5 psig generating oxygen warning, Concentrator inlet pressure moinitored by airframe pressure switch set at 10 psig generating an oxygen caution |
| F-22 | YES (0.6 micron) | 13X (3 beds) | Immobilized | YES | NO | 94%-95% MAX | YES | YES | YES (0.6 micron) | NO | YES | NO | YES | NO | NO | YES | Zirconia | Pressure switch on OBOGS outlet |
| F-35 | Yes (0.4 micron absolute) | 13X (2 beds) | Immobilized | Yes | Volumetric Plenum | 94 Max | Yes | Yes | Yes | No | NO | NO | NO | YES | NO | YES | Zirconia | Pressure switch at inlet to regulator and the system will automatically go to BOS because of low pressure |
| F-15C | | LOX | N/A | NO | NO | 100 Max | N/A | YES | NO | Yes | Yes | No | No | No | Yes | No | No | Pressure switch to sense low pressure (aircraft) |
| F-16 | | LOX | N/A | NO | NO | 100 MAX | N/A | Yes | NO | Yes | YES | NO | NO | NO | YES | NO | NO | Pressure switch to sense low pressure (aircraft) |
| F/A-18 | 93% Efficient at .01 micron | 5AMG | Packed | Sieve bed Outlet | 97 cu/in bottle | 15 psig Inlet Pressure, 92% @ 8.0 lpm, 65% @ 13.1 lpm, 34% 2 35 lpm | No | Yes- Chest Mounted CRU-103 | .4 to .6 micron | No | No | No | No | No Indication of being activated, Possibly need to turn off OBOGS outlet flow when activated. | Concentrator I-Level Test 400 and filter change | Pneumatic BIT prior to flight System Check using TTU-520 | Zirconia oxygen sensor | Cabin Pressure to calculate PPO2 |
| | | | | | | 50 psig Inlet Pressure, 93% @ 13.1 lpm, 50% @ 70 lpm, 40% @ 100 lpm, | | | | | | | | | | | | |
| | | | | | | 80 psig Inlet Pressure, 93% @ 13.1 lpm, 50% @ 70 lpm, 40% @ 100 lpm | | | | | | | | | | | | |
| A-10 | 93% Efficient at .01 micron | 13X(2 beds) OXY-SIV 5 | Packed | Sieve bed outlet | (1 ea) 250 cu/in plenum single seat | 93% @ 26.7 lpm, 34% @ 100 lpm | No | Yes (CRU-98) | .4 to .6 micron | Yes | No | Yes | No | REOS manually activated. Feedback in the form of satfety pressure breathing and REOS pressure gauge | Inlet filter element change at 400 hours | EBIT part of preflight, MBIT every 400 hours with the filter change or during fault isolation resulting from an Oxy-Low indication | Zirconia oxygen sensor in under the panel mounted monitor | Cabin pressure sensor for calculation of PPO2 in panel mounted monitor |
| B-1 | Yes (0.6 micron) | 13X (6 beds) | Immobilized | Yes | No | 94% max | No | Yes | Yes | No | No | No | No | No, manually activated | Filter change | Yes | N/A | Yes, inline on aircraft |
| B-2 | Yes (0.6 micron) | 13X (3 beds) | Immobilized | Yes | Yes | 94% max | Yes | Yes | Yes | No | No | No | No | Yes | Filter change | Yes | Zirconia, OMC | Yes |
| T-6 | 93% Efficient at .01 micron | 13X (2 beds) OXY-SIV 5 | Packed | Sieve bed outlet | ~300 cubic inch (not CLSS) | 90% MIN@ 13.7 LPM | YES | YES | 99.99% efficient @ .1 micron | NO | CRU-60 | NO | NO | NO | Inlet filter element change at 400 hours | Power-up BIT every start up | Zirconia oxygen sensor in monitor concentrator | Aircraft low pressure switch for OBOGS product gas. Cabin pressure sensor for calculation of PPO2 in concentrator based monitor. |
| V-22 | 93% Efficient at .01 micron | (2 beds) OXY-SIV MDX | Packed | Sieve bed outlet | Built in plenum ~250 cubic inch | 80% MIN requirement @ 30 LPM (30K ceiling) | YES | Yes- Chest Mounted CRU-103 | 30 micron | NO | NO | NO | NO | NO | Inlet filter element change at 420 hours | Power-up BIT every start up | Zirconia oxygen sensor in monitor concentrator | Cabin pressure sensor for calculation of PPO2 in concentrator based monitor. |

*Table A-1. Comparison of Various OBOGS in USAF and USN Aircraft.*

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# Appendix B:

# Molecular Characterization – *Neurotoxicity Assessment, Analysis of Symptoms, and Characterization of Chemicals*

## *B.1 Introduction*

One of the two working hypotheses proposed for this Aircraft Oxygen Generation Study addresses the potential for F-22 flight safety being compromised by the presence of toxic levels of contaminants in the air delivered from the on-board oxygen generation system (OBOGS) to the pilot. The presence of high levels of certain classes of chemicals present in jet fuel, jet oil, hydraulic fluid or their pyrolysis products could be a contributing factor in central nervous system (or respiratory) symptoms experienced by pilots and ground crew personnel. This remainder of this Appendix presents a discussion and description of the:

- Neurotoxicity assessment conducted,
- Field measurements obtained,
- Hazard analyses conducted,
- Symptoms (air and ground crew) assessed, and
- Analysis of possible chemical causes.

## *B.2 Neurotoxicity Assessment*

An extensive, multi-step, multi-disciplinary effort was undertaken by personnel from the USAF, Boeing, Lockheed Martin, and others to identify chemicals that might possibly enter a pilot's breathing air on the F-22 and account for acute central nervous system (CNS) effects. The process, termed the Molecular Characterization Matrix (MCM), began with the generation of a list of chemicals known to be present in jet fuel, jet oil, and hydraulic fluids used on the F-22, together with selected chemicals believed to be associated with the pyrolysis or degeneration of these petroleum products. The focus was on chemicals, gases, or aerosols whose presence in life support system (LSS) air was considered plausible by virtue of normal operation of the jet engine, or from leaks in seals, valves, or other conduits.

As of January 24, 2012, 759 chemicals associated with the F-22 had been assessed. Examples of chemical classes assessed in the MCM included:

- Alkanes/Alkenes/Alkynes
- Alcohols/Aldehydes
- Dienes/Esters/Ketones
- Organic Sulfur/Phosphorus compounds
- Total volatile organic compounds

- Other gases (e.g., carbon monoxide, carbon dioxide, nitrogen, argon)

In addition to these classes, the presence of aromatic hydrocarbons (e.g., toluene, benzene), halogenated hydrocarbons (e.g., trichloroethylene, freons), and other gases (e.g., hydrogen cyanide) was assessed.

A Neurotoxicity Assessment Team, consisting of toxicologists and occupational health professionals, narrowed this list of 759 chemicals to a list of 208 chemicals shown to exert acute adverse effects on the CNS in human or experimental animal studies. To date, 126 chemicals in this subset have been detected in ECS air samples from ground and flight tests of the F-22. As an additional step, the Neurotoxicity Assessment Team consulted multiple data sources to identify the lowest concentration of each chemical in air associated with adverse CNS effects in humans or animals.

Data that identified the lowest airborne concentration associated with the onset of central nervous system effects within 30 minutes to several hours was used by the team to derive a "red level" concentration. In most cases, the effect associated with the red level was a mild effect, such as mild central nervous system depression or altered response to external stimuli.

### B.2.1 Consensus Development

For each significant decision in the analysis of CNS effects, input was obtained from three organizations, Lockheed Martin, Boeing, and the United States Air Force (USAF). A summary of the input from each organization was put into a working spreadsheet and then disseminated to the Neurotoxicity Assessment Team. A consensus was determined for each chemical and was listed on the MCM spreadsheet.

### B.2.2 Screening Gate 1

Screening Gate 1 determined whether the CNS effects are a primary concern. At this level, a response of "Yes" was given if there were any CNS effects reported in animal tests or in human observations. If CNS effects have not been reported or if CNS effects were not expected based on the type of chemical, a response of "No" was entered. For example, short chain aldehydes got a "No" response for Screening Gate 1 because they are primarily irritants and not neurotoxic. The most common reasons for assigning a "No" at Decision Gate 1 was because the chemical listed on the MCM is known to be primarily an irritant, or because they were not a specifically identified chemical.

### B.2.3 Screening Gate 2

Screening Gate 2 was intended to determine whether the CNS effects were primarily acute effects. Screening Gate 2 analysis was performed for all chemicals that received a "Yes" response to Decision Gate 1. A "No" response to Decision Gate 2 was given if the evidence for CNS effects was only due to chronic or long-term exposures. Chemicals were deferred if the Neurotoxicity team was told that they were not expected to be on the aircraft. Deferred status is intended to allow for further analysis if it was deemed necessary.

### B.2.4 CNS Effects Analysis

#### *B.2.4.1 Data Sources*

The data sources used to make the determination of concentration associated with CNS effects included exposure limits documentation, databases that provide secondary reviews of the literature, abstracting services, and internal resources. To the extent possible, information was obtained from detailed descriptions so the type of effect and exposure concentration and duration could be identified. CNS effect levels were derived from exposure-effect data from exposures of 30 minutes to several hours.

The data sources consulted included, but were not limited to, authoritative exposure limit documentation such as:

- American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit values (TLV),
- Spacecraft maximum allowable concentrations,
- American Industrial Hygiene Association workplace environmental exposure limits,
- Occupational safety and Health Administration (OSHA) permissible exposure levels (PEL), and
- National Institute for Occupational Safety and Health recommended exposure limits and short term exposure limits.

Also included were

- Toxicological data contained in the National Institute of Occupational safety and Health Registry of Toxic Effects,
- The National Library of Medicine Hazardous Substance Data Base,
- The Canadian Center for Occupational Health and Safety database,
- The National Library of Medicine TOXLINE database, and
- Internal information resources of Boeing, Lockheed Martin, and the USAF.

Data that identified the lowest airborne concentration associated with the onset of CNS effects within 30 minutes to several hours was used by the team to derive a "Red Level" concentration (see Section B.2.4.3 below). In most cases, the effect associated with the red level was a mild effect, such as mild central nervous system depression or altered response to external stimuli.

#### *B.2.4.2 Data Quality*

A wide range of data sources and data quality was used, in order to obtain data for as many chemicals as possible. Data sources ranged from full text or abstracts of published studies to brief descriptions from data compilations. Data from better descriptions were used in preference to data with limited descriptions or data from unverified sources. However, for many chemicals, the data on CNS effects were limited, and any available information was used. In some cases, data were limited to a brief report of CNS effects with limited information about the

effect observed or the experimental design. In the absence of better information, data of this type were used. However, most of the chemicals had data described adequately to determine with good confidence the level associated with CNS effects.

### B.2.4.3 Concentration Associated with CNS Effects (Red Level)

The concentration associated any CNS effects was determined for all chemicals that received a “Yes” response to Screening Gates 1 and 2 (see Sections B.2.2 and B.2.3 above). The concentration used for the red level was the lowest concentration found that was associated with any CNS effect, based on the available data and data summaries. Although data from better descriptions were preferred to data with limited descriptions, the lowest concentration reported to be associated with CNS effects may be based on a source with limited description. When limited information was available, it was assumed that any effect related to central nervous system function was a relevant CNS effect. Effects such as slight dizziness, CNS depression, vertigo, mild tremors, incoordination, or effects on any CNS function test, among many others, were used.

No safety factors were routinely applied to the observed data in order to derive the red level. In cases with a well described concentration-response for CNS effects, the red level was selected to represent a lowest-observed adverse effects level. When more limited data was available, the concentration selected was intended to be the best estimate possible of the threshold for CNS effects. When there was doubt about the appropriate concentration, the lowest of the possible levels was used. The latter decision may introduce some safety margin due to limited information, but a safety factor for limited information, animal information, or based on exposure duration was not routinely applied.

In cases with only animal data it is sometimes difficult to relate an observation to an equivalent human effect or to the equivalent exposure concentration or severity of effect. In these cases, animal effects were assumed to be relevant and to represent potential human effects on an equivalent basis. For example, an animal observation of mild CNS depression or altered response to external stimulus was assumed to relate directly to human CNS effects. In most cases, the effect associated with the red level was a mild effect.

In cases with limited data, it is not possible to determine with certainty the type or severity of the effect associated with the reported concentration. In these cases, it was assumed that the reported effect and concentration from the data that was available were relevant to human CNS effects. It was also assumed that the concentration reported was the lowest concentration associated with CNS effects. These assumptions could not be verified in some cases.

The ACGIH TLV documentation lists the primary effects that were the basis for setting the standard. When CNS effects were listed as one of the effects that were the basis of the exposure limit, the documentation was reviewed to determine whether CNS effects were the most sensitive effects that were the basis of the exposure limit. The TLV was used only when it was clearly associated with mild CNS effects. Otherwise the exposure concentration from studies reporting CNS effects was used.

#### *B.2.4.4 Yellow Level*

The yellow level was assigned by reducing the red level by a factor of 10-100. The yellow level is intended to be a *de minimus* concentration, and to indicate a concentration below which additional effort was not warranted. The yellow level is not associated with CNS effects, and exceeding the yellow level does not indicate a hazard. The yellow level indicates that the chemical may approach concentrations relevant to CNS effects (red level) due to the individual chemical or additive effects, so continued attention is appropriate.

## *B.3 Field Measurements*

A series of field measurements were undertaken in ground and flight tests of F-22 aircraft to quantify concentrations of the narrowed list of MCM chemicals that were present in the environmental control system, with a particular focus on levels in air sampled at both the OBOGS inlet and outlet. Multiple engine sources and ECS configurations (using incident and non-incident engines and/or aircraft) and OBOGS were utilized for the data collection. The sampling media included sorbent tubes and air collected in summa canisters. Analytical methodology included Environmental Protection Agency (EPA) TO-15 (utilizing gas chromatography/mass spectrometry to quantify 75 volatile organic compounds with known standards, and to tentatively identify and quantify other compounds by comparison with spectral libraries), EPA TO-15 (modified) to quantify C3-C12 hydrocarbons, EPA 25C to measure carbon monoxide (CO) and carbon dioxide ($CO_2$), EPA 3C (modified) to quantify oxygen, nitrogen, and argon, and EPA TO-11 to quantify aldehydes. Direct reading instruments were also utilized to measure certain contaminants, such as carbon monoxide, cyanide, and certain gases. The maximum value of each analyte identified during the course of the entire testing program was used to populate the MCM.

During the course of the field measurement program, it was determined that initial tests conducted at Elmendorf Air Force Base (AFB) and Edwards AFB were subject to chemical artifacts arising from the use of isopropyl alcohol or Freon-based cleaning agents to clean the valves and tubing of the test collection equipment. Subsequent tests avoided the potential for such artifacts by using heated oxygen to clean and purge the test equipment.

A few additional findings pertaining to the air measurements conducted on the F-22 merit brief discussion. A direct reading instrument, termed a ppbRAE, was used to measure total volatile organic compounds (VOCs) on the F-22 during ground and flight tests. Excluding transient peaks during engine start-up or shut-down, the maximum level of VOCs measured in ground and flight breathing air delivered to the pilots via the breathing regulator Breathing Regulator Anti-G (BRAG) valve was in the range of 1-5 parts per million (ppm). Steady state levels were typically below 1 ppm. These values, which are consistent with measurements routinely obtained aboard commercial aircraft[8], are far below the values associated with acute CNS symptoms. The summa canister analyses on several F-22 tests detected the presence of tentatively identified and unidentified fluorocarbons, typically at an aggregate concentration of less than 1 milligram per cubic meter ($mg/m^3$). By way of comparison, it may be noted that

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[8] Crump, D., et. al. "Aircraft Cabin Air Sampling Study (Parts 1 and 2)."

1-hour Spacecraft Maximum Allowable Concentration (SMAC) concentrations and TLVs for halogenated anesthetic gases are generally on the order of hundreds of $mg/m^3$ of air. The source of these fluorocarbons, which at the levels detected would not be expected to cause acute CNS depression, is undetermined. The possibility exists that the presence of fluorocarbons may be an artifact of the measurement collection equipment, in that they were detected in similar concentrations on air drawn through the test equipment prior to its installation on the F-22. Early direct measurement of post-BRAG valve air of an incident F-22 aircraft during a ground test in the spring of 2009 failed to detect any fluorocarbons.

Table B-1 and B-2 (below) identify specific VOCs detected in OBOGS inlet and outlet air. The maximum concentration measured in OBOGS outlet breathing air in either ground or flight tests at Elmendorf AFB and Edwards AFB (on days in which no cleaning agents were used to clean and purge the air collection equipment) is shown in Column 2. Column 3 depicts the corresponding red limit concentration for acute CNS effects associated with each chemical, and Column 4 indicates the *hazard quotient* (the maximum measured concentration divided by the red limit).

The analysis of collected pre- and post-OBOGS air samples from ground and flight testing reveals no VOCs in breathing air at a concentration that represents and acute risk to health. To date, none of the chemicals detected in air supplied to the OBOGS or breathing air, including metabolic toxicants such as carbon monoxide, cyanide, or organophosphates, have been measured at concentrations associated with acute CNS symptoms or at levels that present an acute hazard to the pilot. Further, the analysis of the incident pilot clinical surveillance data to date reveals no alterations from baseline or normal values.

## B.4 Hazard Analysis

Because the chemicals identified were all volatile organic compounds capable of exerting depressant effects on the CNS through a common mode of action, it is appropriate to calculate a *hazard index* which sums the *hazard quotients (*the maximum measured concentration divided by the red limit), according to the formula:

$$\text{Hazard Index} = \sum (C_i / [\text{red limit}]_i)$$

where "$C_i$" is the maximum measured concentration of each chemical, and "red $\text{limit}_i$" is that chemical's respective red limit concentration. A hazard index less than 1.0 indicates that no acute adverse effects would be expected. A hazard index greater than 1.0 indicates that adverse effects are possible.

Table B-1 (below) shows the maximum concentrations for specific VOCs as measured at the OBOGS inlet during flight and ground testing. The Red Limit Concentrations for developing hazard quotients for each of the volatile organic compounds are also shown along with the associated hazard quotients. Note the overall Hazard Index, as derived from the summation of the individual Hazard Quotients is 0.21.

Table B-2 (below) provides similar data for the corresponding flight and ground test data taken at the OBOGS outlet. The overall Hazard Index at the OBOGS outlet is 0.36, well below the value of 1.0 at which adverse effects are considered possible. This provides reassurance that the chemicals detected in OBOGS outlet breathing air sampled from the F-22 ground and flight test to date were unlikely to have accounted for CNS symptoms.

Note that the concentrations (OBOGS inlet/outlet) are in parts per billion by volume (ppbV).

| Chemical Name | Times Detected (1 = at least once) | Maximum Concentration at OBOGS Inlet (ppbV) | Red Limit Concentration (ppbV) | Hazard Quotient |
|---|---|---|---|---|
| Argon | 20 | 37,000,000 | 330,000,000 | 0.1121 |
| $CO_2$ carbon dioxide | 29 | 950,000 | 20,000,000 | 0.0475 |
| 2-Propanol (Isopropyl Alcohol) (1-100) | 42 | 8,200 | 400,000 | 0.0205 |
| Carbon Disulfide | 1 | 20 | 1,000 | 0.02 |
| C8 as n-Octane | 6 | 1,400 | 1,000,000 | 0.0014 |
| 1,3-Dichloro-1,1,2,2,3-pentafluoropropane (HCFC-225cb) | 7 | 1,205 | 1,000,000 | 0.0012 |
| Acetonitrile | 8 | 45 | 40,000 | 0.0011 |
| alpha-Cumyl Alcohol | 7 | 8.3 | 10,000 | 0.0008 |
| Toluene | 46 | 40 | 50,000 | 0.0008 |
| 2-Ethyl-1-hexanol | 7 | 7.3 | 10,000 | 0.0007 |
| tert-Butanol | 1 | 18.8 | 50,000 | 0.0003 |
| 4-Methyl-2-pentanone | 3 | 8.6 | 25,000 | 0.0003 |
| Ethyl Acetate | 30 | 110 | 400,000 | 0.0003 |
| Acetone (0-1000) | 38 | 150 | 1,000,000 | 0.0002 |
| 1,2,4-Trimethyl benzene | 7 | 11 | 100,000 | 0.0001 |
| m,p-Xylenes | 7 | 9.7 | 100,000 | <0.0001 |
| C12 as n-Dodecane | 9 | 94 | 1,000,000 | <0.0001 |
| C13H28 Branched Alkane | 7 | 82 | 1,000,000 | <0.0001 |
| Benzene | 9 | 4.1 | 50,000 | <0.0001 |
| C11 as n-Undecane | 12 | 190 | 2,400,000 | <0.0001 |
| C11H24 Branched Alkane | 5 | 72 | 1,000,000 | <0.0001 |
| C10 as n-Decane | 11 | 62 | 1,000,000 | <0.0001 |
| C9 as n-Nonane | 7 | 98 | 1,600,000 | <0.0001 |
| Cyclohexane | 2 | 15 | 250,000 | <0.0001 |
| 2,4-Dimethylheptane | 5 | 52 | 1,000,000 | <0.0001 |
| 1,3,5-Trimethylbenzene | 6 | 4.4 | 100,000 | <0.0001 |
| o-Xylene | 6 | 4.3 | 100,000 | <0.0001 |
| 4-Ethyltoluene | 6 | 2.1 | 50,000 | <0.0001 |
| 2-Butanone (MEK) | 1 | 7.8 | 200,000 | <0.0001 |
| 1,2,4-Trimethylbenzene | 1 | 3.8 | 100,000 | <0.0001 |

| | | | | |
|---|---|---|---|---|
| Methyl tert-Butyl Ether | 1 | 1.8 | 50,000 | <0.0001 |
| C4 as n-Butane | 10 | 340 | 10,000,000 | <0.0001 |
| C12H26 Branched Alkane | 18 | 31 | 1,000,000 | <0.0001 |
| 4-Methyl octane | 9 | 28.6 | 1,000,000 | <0.0001 |
| Propene | 37 | 1,500 | 64,000,000 | <0.0001 |
| 2-Methyl-1-pentene | 2 | 20 | 1,000,000 | <0.0001 |
| Naphthalene | 7 | 1 | 50,000 | <0.0001 |
| C6 as n-Hexane | 1 | 2.8 | 250,000 | <0.0001 |
| C7 as n-Heptane | 4 | 11 | 1,000,000 | <0.0001 |
| Ethylbenzene | 6 | 1 | 100,000 | <0.0001 |
| C10H22 Branched Alkane | 4 | 8.6 | 1,000,000 | <0.0001 |
| C15H32 Branched Alkane | 3 | 7.1 | 1,000,000 | <0.0001 |
| Methyldecalin Isomer | 1 | 0.7 | 100,000 | <0.0001 |
| C12H24 Compound | 1 | 5.7 | 1,000,000 | <0.0001 |
| 2,4-Dimethyl-1-heptene | 1 | 5 | 1,000,000 | <0.0001 |
| C3 as Propane | 16 | 1,400 | 280,000,000 | <0.0001 |
| Styrene | 2 | 0.2 | 50,000 | <0.0001 |
| 1,3-Butadiene | 6 | 7.3 | 2,000,000 | <0.0001 |
| n-Nonane | 1 | 5.3 | 1,600,000 | <0.0001 |
| Dodecane | 12 | 6.5 | 2,400,000 | <0.0001 |
| Cumene | 4 | 0.5 | 200,000 | <0.0001 |
| Undecane | 9 | 5.5 | 2,400,000 | <0.0001 |
| n-Octane | 1 | 2 | 1,000,000 | <0.0001 |
| C5 as n-Pentane | 6 | 62 | 32,000,000 | <0.0001 |
| 2-Hexanone | 2 | 1.6 | 1,000,000 | <0.0001 |
| C11H22 Compound | 1 | 1.3 | 1,000,000 | <0.0001 |
| n-Heptane | 1 | 0.8 | 1,000,000 | <0.0001 |
| n-Propylbenzene | 5 | 0.6 | 2,000,000 | <0.0001 |
| Propylcyclohexane | 1 | 1.7 | 7,500,000 | <0.0001 |
| Isobutene Isobutylene | 5 | 41 | 198,000,000 | <0.0001 |
| | | | **Hazard Index** | **0.21** |

*Table B-1. Hazard Quotients and Hazard Index for Chemicals Measured at OBOGS Inlet.*

| Chemical name | Times Detected (1 = at least once) | Maximum Concentration at OBOGS Outlet (ppbV) | Red Limit Concentration (ppbV) | Hazard Quotient |
|---|---|---|---|---|
| Argon | 21 | 46,000,000 | 330,000,000 | 0.1394 |
| C6 as n-Hexane | 1 | 12,000 | 250,000 | 0.048 |
| Toluene | 70 | 2,100 | 50,000 | 0.042 |
| 2-Butanone (MEK) | 1 | 7,800 | 200,000 | 0.039 |
| 2-Propanol (Isopropyl Alcohol) (1-100) | 59 | 11,000 | 400,000 | 0.0275 |
| $CO_2$ carbon dioxide | 18 | 510,000 | 20,000,000 | 0.0255 |
| n-Hexane | 1 | 3,700 | 250,000 | 0.0148 |
| C7 as n-Heptane | 1 | 11,000 | 1,000,000 | 0.011 |
| C8 as n-Octane | 16 | 3,000 | 1,000,000 | 0.003 |
| Cyclohexane | 1 | 640 | 250,000 | 0.0026 |
| 2-Ethyl-1-hexanol | 11 | 16 | 10,000 | 0.0016 |
| alpha-Cumyl Alcohol | 7 | 11 | 10,000 | 0.0011 |
| Acetone (0-1000) | 42 | 650 | 1,000,000 | 0.0007 |
| Methyldecalin Isomer | 1 | 43 | 100,000 | 0.0004 |
| tert-Butanol | 1 | 20 | 50,000 | 0.0004 |
| 1,3-Dichloro-1,1,2,2,3-pentafluoropropane (HCFC-225cb) | 16 | 350 | 1,000,000 | 0.0003 |
| m,p-Xylenes | 19 | 26 | 100,000 | 0.0003 |
| 1,2,4-Trimethyl benzene | 7 | 4 | 100,000 | <0.0001 |
| C12 as n-Dodecane | 8 | 94 | 1,000,000 | <0.0001 |
| Ethanol (50-1000) | 1 | 87 | 1,000,000 | <0.0001 |
| C10 as n-Decane | 13 | 83 | 1,000,000 | <0.0001 |
| Ethyl Acetate | 40 | 33 | 400,000 | <0.0001 |
| Benzene | 7 | 4 | 50,000 | <0.0001 |
| 4-Methyl-2-pentanone | 2 | 2 | 25,000 | <0.0001 |
| n-Heptane | 1 | 80 | 1,000,000 | <0.0001 |
| C11 as n-Undecane | 11 | 190 | 2,400,000 | <0.0001 |
| C13H28 Branched Alkane | 5 | 78 | 1,000,000 | <0.0001 |
| C9 as n-Nonane | 7 | 98 | 1,600,000 | <0.0001 |
| C12H26 Branched Alkane | 17 | 58 | 1,000,000 | <0.0001 |
| 2,4-Dimethylheptane | 8 | 46 | 1,000,000 | <0.0001 |
| Acetonitrile | 4 | 2 | 40,000 | <0.0001 |
| 1,3,5-Trimethylbenzene | 10 | 4 | 100,000 | <0.0001 |
| 4-Methyl octane | 11 | 42 | 1,000,000 | <0.0001 |
| 1,2,4-Trimethylbenzene | 1 | 4 | 100,000 | <0.0001 |
| C12H24 Compound | 1 | 37 | 1,000,000 | <0.0001 |

| | | | | |
|---|---|---|---|---|
| o-Xylene | 9 | 3 | 100,000 | <0.0001 |
| Propene | 43 | 1,800 | 64,000,000 | <0.0001 |
| Naphthalene | 2 | 1 | 50,000 | <0.0001 |
| 2-Methyl-1-pentene | 1 | 22 | 1,000,000 | <0.0001 |
| Ethylbenzene | 8 | 2 | 100,000 | <0.0001 |
| C11H24 Branched Alkane | 7 | 18 | 1,000,000 | <0.0001 |
| n-Nonane | 1 | 17 | 1,600,000 | <0.0001 |
| Styrene | 1 | 1 | 50,000 | <0.0001 |
| C5 as n-Pentane | 4 | 330 | 32,000,000 | <0.0001 |
| Tetrahydrofuran (THF) | 1 | 2 | 190,000 | <0.0001 |
| C15H32 Branched Alkane | 6 | 9 | 1,000,000 | <0.0001 |
| n-Octane | 1 | 4 | 1,000,000 | <0.0001 |
| C4 as n-Butane | 8 | 35 | 10,000,000 | <0.0001 |
| 4-Ethyltoluene | 1 | 0.2 | 50,000 | <0.0001 |
| Dodecane | 13 | 4 | 2,400,000 | <0.0001 |
| 2-Hexanone | 1 | 1.4 | 1,000,000 | <0.0001 |
| C3 as Propane | 13 | 340 | 280,000,000 | <0.0001 |
| 1,3-Butadiene | 1 | 1.3 | 2,000,000 | <0.0001 |
| Undecane | 12 | 1.3 | 2,400,000 | <0.0001 |
| Isobutene Isobutylene | 2 | 40 | 198,000,000 | <0.0001 |
| n-Propylbenzene | 1 | 0.15 | 2,000,000 | <0.0001 |
| | | | **Hazard Index** | **0.36** |

*Table B-2. Hazard Quotients and Hazard Index for Chemicals Measured at OBOGS Outlet.*

## B.5 Symptom Analysis and Possible Causes

Recent ground and flight testing of the F-22 LSS has demonstrated that numerous volatile organic chemicals that are constituents of ambient air, polyalphaolefin, and Petroleum, Oils and Lubricants, and are consistently present at the inlet and outlet of the OBOGS. Such contamination of the breathing air is assumed to be typical of LSS utilizing engine bleed air. The presence of such contaminants is also well documented in the commercial airline industry. The LSS of the F-22 was not designed to filter volatile contaminants from bleed air; however, recent testing indicates OBOGS can reduce the concentration of some chemicals in the product gas while concentrating others such as argon. The contaminants measured were found at low levels and were determined to be below the concentrations associated with health risks in humans.

### B.5.1 CNS Symptoms

Notwithstanding the levels of contaminants measured, the Study Panel heard evidence that F-22 pilots and ground personnel reported CNS symptoms consistent with hypoxia or exposure to a toxic substance. A molecular characterization effort that is ongoing has been designed to identify all potential airborne toxicants in the F-22, determine the ability of these chemicals to enter the breathing air, and the ability of these chemicals, either individually or in

aggregate, to cause acute CNS toxicity in humans. The potential for a toxicant entering the breathing air at a hazardous concentration is not ruled out as a cause of pilot symptoms; however evidence for this possibility was not found in ground and flight testing to date.

The neurons of the central nervous system have little capacity for anaerobic metabolism and thus are exquisitely sensitive to inadequate oxygen (hypoxia) or a lack of oxygen (anoxia). The term anoxic anoxia refers to a primary lack of blood oxygen in the presence of an otherwise adequate blood supply to the tissues. This condition can be caused by a lack of oxygen in the breathing air, respiratory failure or a decreased oxygen delivery capacity of the blood as in the case of CO poisoning. Ischemic anoxia is caused by decreased arterial pressure, decreased cardiac output, or by vascular occlusion. Cytotoxic anoxia results from an inhibition of cellular metabolism at the tissue and cellular level in the presence of adequate supply of both blood and oxygen. This later condition can result from exposure to toxic levels of metabolic inhibitors such as cyanide. In toxicology, anoxia can be a prototype for CNS injury as many neurotoxicants mimic anoxia to some degree. The symptoms of hypoxia can also be confused with the signs of acute solvent intoxication as discussed below.

There are a large number of VOCs that can depress CNS function causing what are known as "acute solvent effects." A list of over 500 chemicals that can cause acute CNS Solvent Syndrome and their toxicological information has been published on TOXNET. Solvents (including gas anesthetics) enter the CNS primarily through the respiratory track and, due to their high lipid solubility, rapidly enter the blood stream, and then pass through the blood brain barrier into the CNS. Their effect is primarily to slow the propagations of action potentials along nerve cells and thus depress CNS function. Symptoms of acute CNS Solvent Syndrome caused by exposure to toxic levels of these chemicals can cause signs such as difficulty concentrating, confusion, dizziness, fatigue, headache, inebriation, irritability, impaired speech, lethargy, stupor, coma, and death. Many of these toxic effects can be reversed by removing the individual from the toxic environment into fresh air. It is this group of compounds, VOCs, which are the major constituents of jet fuels, engine oils, lubricating fluids, and hydraulic fluids. Like with any substance, the dose of the substance to which an individual is exposed, the route of exposure, and the sensitivity of the individual determines if the exposure will cause toxicity. The majority of VOCs have threshold values below which no clinical signs of toxicity are expected to occur. For many VOCs encountered in the work place, occupational exposure levels have been established that are designed to provide significant margins of safety for individuals who are exposed in their daily activities. In fact, VOCs at some level are present in atmospheric air samples and are significant constituents of air pollution and smog.

In most of the recent cases of hypoxia or hypoxia like incidents reported during F-22 operations, the signs and symptoms of the affected pilots were determined to be consistent with hypoxia caused by delivery of inadequate levels of oxygen in the breathing air. However, the causes of a number of breathing air anomalies remain unknown. When hypoxia develops gradually, the symptoms may include difficulty concentrating, headache, fatigue, shortness of breath, a feeling of euphoria and nausea. In hypoxia of very rapid onset, changes in vision, levels of consciousness, seizures, coma, and death occur. Pilots train to quickly recognize this condition and to respond with deployment of emergency oxygen systems. The symptoms typically disappear promptly upon receipt of adequate oxygen. Hypoxia caused by exposure to toxic levels of certain metabolic poisons such as CO and cyanide, on the other hand, prevent the delivery of oxygen to the tissues and the resultant CNS effects of acute high dose exposure are

not rapidly reversible. Furthermore, exposure to these two compounds results in formation of specific biomarkers of toxicity that can be readily measured in clinical samples. No clinical samples collected to date from incident personnel have shown such abnormalities.

### B.5.2 Respiratory Symptoms

The Study Panel heard anecdotal reports that F-22 pilots frequently experience respiratory complaints within minutes to hours after completion of a sortie. The complaints were dominated by the occurrence of a mild to moderate non-productive cough unaccompanied by fever or other systemic symptoms. The Study Panel heard preliminary results of a formal survey of the F-22 and F-16 pilot community in which 65% of F-22 pilot respondents reported the occurrence of a cough during or shortly after some sorties, compared to 16% of F-16 pilot respondents. In addition, a significant number of F-22 pilots reported symptoms consistent with chest tightness. The temporal pattern of these respiratory symptoms does not appear to be consistent with acceleration atelectasis, a well-described entity in aviation medicine that is typically associated with the rapid onset of short-lived cough, chest tightness, or dyspnea. Consequently, a formal clinical and epidemiological investigation of the respiratory complaints is recommended. Irritant effects of ozone, volatile organic compounds, and inorganic gases and fine particulates have been associated with dry cough and chest tightness. Immunological responses, including antigen induced asthma or hypersensitivity pneumonitis, may also be associated with symptoms of this nature.

## *B.6 Possible Causes*

The following sections address selected chemicals (VOCs and others) that the Study Panel found to be of primary interest as possible causes of various respiratory and CNS-type symptoms experienced by F-22 Raptor air and ground crew.

### B.6.1 Carbon Monoxide

Carbon Monoxide has a well-characterized dose-dependent capacity to cause decrements in central nervous system function that may be accompanied by symptoms of lightheadedness, dizziness, diminished capacity to concentrate, and headache. Accordingly, the potential role of carbon monoxide as a cause of hypoxia-like incidents has been carefully considered by the AOG Study Panel. Carbon monoxide exposure to F-22 aircrew has been assessed by two independent approaches: (1) real-time measurement of carbon monoxide using multi-RAE or Graywolf TG-501 direct reading instruments on the flight-line, or in the cockpit or OBOGS outlet during ground or flight operations, and (2) post-exposure measurement of carboxyhemoglobin in the blood of personnel. The flight-line measurements found CO values to average less than 15 ppm, with transient excursions to 15 to 50 ppm in the immediate vicinity of engine exhaust. Cockpit and OBOGS outlet measurements during ground and flight operations averaged less than 2 ppm, with transient spikes in the cockpit of up to 8.5 ppm during transition points of ground operation including auxiliary power unit (APU) on/off, engine on/off, or canopy open/close. Carboxyhemoglobin measurements of aircrew were almost always less than 3 percent, with one confirmed value of 4 percent.

Extensive human studies have examined the relationship between carbon monoxide exposure and carboxyhemoglobin levels, and in turn, the impact of carboxyhemoglobin levels on central nervous symptoms and human performance. The EPA published an extensive assessment

of the health effects of low-level carbon monoxide exposure.[9] With respect to the impact of carbon monoxide on human behavior and neurological performance, the EPA concluded:

> In summary, no reliable evidence demonstrating decrements in neural or behavioral function in healthy young adult humans has been reported for carboxyhemoglobin levels below 20%, and even those studies are untested by replication. The low carboxyhemoglobin behavioral effects that have sometimes been reported cannot be taken at face value because they are not reliably repeatable, and they do not fit into wider range, dose-effect patterns reported in other studies. It is more reasonable to conclude that no statistically detectable behavioral impairments occur until carboxyhemoglobin exceeds 20 to 30%. Significant behavioral impairments in healthy individuals should not be expected until carboxyhemoglobin levels exceed 20%.[10]

In like manner, a meta-analysis[11] analyzed data from multiple controlled animal experiments, as well as published human data on hypoxic hypoxia, based on the premise that the neurotoxicity of carbon monoxide is largely attributable to diminished oxygen delivery to the brain. This analysis concluded that "for healthy sedentary persons, 18–25% carboxyhemoglobin would be required to produce a 10% decrement in behavior," (i.e., 10% change in neurobehavioral test performance). A 10% decline from average values would represent a relatively small effect that would still be well within the normal spectrum of human performance.

Controlled human study of the relationship between carbon monoxide inhalation and carboxyhemoglobin levels have yielded models, such as the Coburn, Forster, and Kane (CPK) equation that have been validated during rest and exercise. The CPK equation predicts that the level of carbon monoxide exposure resulting in a carboxyhemoglobin value of 20% would include 1,000 ppm for approximately 40 minutes, 500 ppm for approximately 90 minutes, or 200 ppm for approximately 400 minutes.[12] These values exceed the pattern of carbon monoxide exposure documented during all phases of F-22 operation by at least two orders of magnitude. Based on all of the foregoing, it may be concluded that CO exposure to F-22 pilots or ground crew is far below that capable of causing the overt central nervous system symptoms that have been the subject of current investigation.

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[9] United States Environmental Protection Agency. "Air Quality Criteria for Carbon Monoxide (EPA 600/P-99/001F)."

[10] Ibid.

[11] Benignus, V. "Behavioral Effects of Carbon Monoxide: Meta Analyses and Extrapolation."

[12] Peterson, J., & Stewart, R. "Predicting the Carboxyhemoglobin Levels Resulting from Carbon Monoxide Exposures."

### B.6.2 Carbon Dioxide

Carbon dioxide is present in the atmosphere from natural and anthropogenic sources (e.g. the combustion of fossil fuels). The global average marine surface atmospheric concentration was estimated to be 389 ppm (slightly less than 0.04%) in 2010.[13] Health effects potentially associated with $CO_2$ inhalation by servicemen in military settings have been evaluated in two major reviews.[14,15] As described in both documents, sufficiently elevated concentrations of carbon dioxide can result in acute CNS and constitutional symptoms, including decrements in visual and auditory acuity, impaired cognition, headache, and shortness of breath. By activating central and peripheral chemoreceptors, carbon dioxide concentrations as low as 1.0% elicit a hyperventilatory response. That response is not a toxic effect per se, and at low levels acclimatization occurs. A National Research Council (NRC) report on Spacecraft Maximum Allowable Concentrations[16] concluded that mild CNS depression can occur after acute exposure to atmospheres containing 5% $CO_2$. The no-observed adverse effect level for acute exposure (hours to days) was 4%; that for sub-chronic exposures (days to weeks) was 3%. After application of a safety margin adjusting for the small number of subjects in the key studies, the 1 hour and 24 hour SMAC was set at 1.3% $CO_2$ (i.e. 13,000 ppm), with CNS depression and visual disturbance as the target toxicity. The 2007 NRC report[17] took note of two small studies (each n = 3) that found a subclinical impact on visual tracking and depth perception after acute (1 hour) exposure to 2.5% $CO_2$, and designated this as an acute lowest observed adverse effect level. Because the effect was subtle, reversible, and of questionable toxicologic and operational significance, no safety margin was applied, and the 1 hour and 24 hour Emergency Exposure Guidance Level was set at 2.5% $CO_2$ (25,000 ppm). The OSHA permissible exposure limit for $CO_2$ as an 8-hour time weighted average is 5,000 ppm, which OSHA sought unsuccessfully to raise to 10,000 ppm in 1989.

Carbon dioxide concentrations in the F-22 have been measured using two different methods. Summa canisters were used to sample for $CO_2$ at the OBOGS inlet and outlet in flight tests with numerous configurations in the summer of 2011. Paired measurements typically demonstrated a significant decline in $CO_2$ measured at the outlet compared to the inlet. The maximum (unpaired) inlet and outlet $CO_2$ concentrations were 950 ppm and 510 ppm, respectively. Outlet $CO_2$ concentrations less than 100 ppm were frequently observed. In the fall

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[13] Blasing, T. "Recent Greenhouse Gas Concentrations."

[14] National Research Council (Committee on Toxicology). "Carbon Dioxide. In Emergency and Continuous Exposure Guidance Levels for Submarine Contaminants."

[15] Wong, K. "Carbon Dioxide. In Subcommittee on Spacecraft Maximum Allowable Concentrations National Research Council, Spacecraft Maximum Allowable Concentrations for Selected Airborne Contaminants (Volume 2)."

[16] Ibid.

[17] National Research Council (Committee on Toxicology). "Carbon Dioxide. In Emergency and Continuous Exposure Guidance Levels for Submarine Contaminants."

of 2011, the Technical Assistance ("107") Team used a real-time instrument to obtain continuous measurements of $CO_2$ in the cockpit of incident F-22 aircraft during ground tests. Spikes in $CO_2$ up to 2,500 ppm were observed for a few minutes during transitional events such as such as APU start/stop, engine on/off/military power, canopy open/close, followed by rapid declines to 100 to 1,500 ppm with continued engine operation. It may be seen that the $CO_2$ measurements obtained in F-22 have been one to two orders of magnitude lower than those associated with even subclinical CNS effects. Based on these results, $CO_2$ exposure from an external source is not suspected of having contributed to acute CNS effects among F-22 air crew members.

### B.6.3 Ozone

Ozone merits consideration as a potential contributor to respiratory complaints experienced by F-22 pilots. At sufficiently high doses, ozone exposure has been associated with respiratory complaints that commonly include cough, chest tightness, and discomfort on deep inspiration.[18] Exposure to atmospheric ozone increases at higher altitudes (e.g., at or above 32,000 feet), and at high latitudes (e.g., toward the polar regions). In this regard, it is notable that preliminary findings of a survey of F-22 pilots found increased respiratory complaints after high altitude sorties. Short-term tolerance to the respiratory effects of ozone develops with consecutive daily exposure.[19] This might contribute to a variable association between ozone exposure and respiratory complaints among pilots whose flight schedules and flight profiles vary across a week.

Without catalysts that eliminate ozone, cabin ozone concentrations in commercial aircraft not uncommonly reach levels ranging from those associated with subclinical pulmonary inflammation in susceptible individuals (0.06 ppm) to overt symptoms in many individuals (at or above 0.25 ppm).[18,20] Levels of ozone as high as 1.0 ppm have been recorded in the cabin air of some aircraft.[21] Federal Aviation Administration aircraft air quality operating standards for ozone are at or below 0.25 ppm (ceiling) when operating above 32,000 feet, and at or below 0.1 ppm Time Weighted Average during any 4-hour interval above 27,000 feet. Compliance with these standards on commercial aircraft requires use of a catalyst. Such devices are not present on the F-22. The extent to which the F-22's jet engine compressors would reduce the ozone concentration in bleed air below atmospheric levels, and the extent to which avionics might produce ozone, have not been investigated.

In what was termed a "limited screen of cockpit air," passive samplers were utilized to measure in-flight levels of ozone during 12 F-22 sorties at Langley AFB in the late winter of

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[18] McDonnell, W., et. al. "Ozone-Induced Respiratory Symptoms: Exposure-Response Models and Association with Lung Function."

[19] Gong, H., et. al. "Attenuated Response to Repeated Daily Ozone Exposures in Asthmatic Subjects."

[20] Kim, C., et. al. "Lung Function and Inflammatory Responses in Healthy Young Adults Exposed to 0.06 ppm Ozone for 6.6 Hours."

[21] Spengler, J., et. al. "Ozone Exposures During Trans-Continental and Trans-Pacific Flights."

2011.[22] The average of 12 samples was 0.016 ppm; the range was not reported. The altitude and latitude associated with these sorties was not provided. Interestingly, passive ozone sampling on the flight line yielded an average ozone concentration of 0.14 ppm.

A laboratory investigation undertaken by the USAF School of Aerospace Medicine found that an OBOGS operated at a simulated aircraft altitude of 40,000 feet and a cabin altitude of 8,000 feet diminished ozone levels between inlet gas and product gas by three orders of magnitude.[23] It was predicted that at a worse case inlet concentration of 16 ppm ozone, the outlet air would contain 0.038 ppm ozone, a level associated with olfactory awareness but devoid of adverse respiratory effects. It was recommended that valves and other components of an OBOGS be constructed of materials resistant to the corrosive oxidizing effect of high ozone concentrations. Based on all of the foregoing, ongoing investigations of respiratory complaints experienced by F-22 pilots should examine the potential contributory role of ozone, and should consider more extensive characterization of aircrew ozone exposure.

### B.6.4 Argon

Like other oxygen concentration systems utilizing synthetic zeolites, the F-22 OBOGS concentrates argon, an inert gas that naturally occurs in the atmosphere at a concentration of 0.94% by volume. As with oxygen, the degree of concentration is approximately 4- to 5-fold, and as expected, the maximum argon concentration detected in F-22 OBOGS outlet (product) gas was 4.6 percent. Adverse health effects associated with long-term inhalation of air with this concentration of argon have not been reported. The Department of Energy (DoE) TEEL-0 value (Temporary Emergency Exposure Limit) for argon, defined as a “threshold concentration below which most people will experience no appreciable risk of health effects” is 60,000 ppm, or 6 percent.[24] Argon has a density greater than oxygen, but at the concentrations of less than 7 percent customarily found in oxygen concentrators, it does not alter the flow characteristics of air or appreciably increase the work of breathing.[25,26]

At normobaric pressure, argon acts as a simple asphyxiant gas. It becomes hazardous only at concentrations that are high enough to displace a significant proportion of oxygen in the inhaled atmosphere. The DoE TEEL-2 value for argon, defined as “the maximum airborne concentration below which it is believed that nearly all individuals could be exposed without experiencing or developing irreversible or other serious health effects or symptoms which could

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22 United States Air Force School of Aerospace Medicine. “Consultative Letter: Initial Screening of F-22 Raptor Fleet for Environmental Contaminants that May cause “Hypoxia-Like” Symptoms.”

23 Miller, G. “Ozone Contaminant Testing of a Molecular Sieve Oxygen Concentrator (MSOC).”

24 United States Department of Energy. “Temporary Emergency Exposure Limits for Chemicals: Methods and Practice (DOE-HDBK-1046).”

25 Friesen, R. “Oxygen Concentrators and the Practice of Anaesthesia.”

26 Shulagin, Y., et. al. “Effects of Argon on Oxygen Consumption in Humans During Physical Exercise Under Hypoxic Conditions.”

impair an individual's ability to take protective action" is 230,000 ppm, or 23 percent.[27] If normobaric gas mixtures are formulated to provide an adequate concentration of oxygen, much higher concentrations of argon can be tolerated without adverse effects. In an experimental protocol, no CNS effects were experienced by 4 Navy divers breathing a normobaric mixture of 69 percent argon, 11 percent nitrogen, and 20 percent oxygen for 2 minutes.[28] Ten subjects had no decrement in computational ability or subjective rating of narcosis after breathing a normobaric mixture of 80% argon and 20% oxygen for 2 to 8 minutes.[29] In a study of staged decompression simulating extravehicular space activity by astronauts, 40 volunteers were administered either 100% oxygen or a mixture of 62% argon and 38% oxygen (ARGOX) for 4 hours prior to full decompression to a 3.5 psia atmosphere.[30] The ARGOX mixture was associated with an increased occurrence of symptoms of decompression sickness, but acute central nervous deficits were not reported.

When delivered at *elevated atmospheric pressure*, air mixtures enriched in argon have depressant effects on the central nervous system. In the study[28] cited above, effects of argon on the cognition of divers were apparent at 4 atmospheres (atm) pressure; a similar narcosis-like effect was evident in animals exposed to argon at 4 atm.[31] Argon at approximately 15 to 20 atm pressure produces frank anesthesia,[32,33] an effect possibly mediated by agonist effects on respond to the gamma-aminobutyric acid (GABA) receptors in the brain. Recent studies have suggested a metabolic effect of high concentrations of argon delivered at normobaric pressure. Human volunteers inhaling atmospheres containing either 85% argon and 15% oxygen, or 30% argon and 15% oxygen and 55% nitrogen, exhibited a slight increase in oxygen consumption during exercise, without a decrement in capillary hemoglobin oxygen saturation compared to exercise on 85% nitrogen and 15% oxygen.[34] This was interpreted as a protective ability of argon to enhance the efficiency of oxygen utilization by tissues during hypoxic stress. Recently, a neuro-protective role of 50% argon and 50% oxygen following cerebral ischemia was

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[27] United States Department of Energy. "Temporary Emergency Exposure Limits for Chemicals: Methods and Practice (DOE-HDBK-1046)."

[28] Behnke, A., & Yarbrough, O. "Respiratory Resistance, Oil-Water Solubility, and Mental Effects of Argon, Compared with Helium and Nitrogen."

[29] Fowler, B., & Ackles, K. "Narcotic Effects in Man of Breathing 80-20 Argon-Oxygen and Air under Hyperbaric Conditions."

[30] Pilmanis, A., et. al. "Staged Decompression to 3.5 PSI Using Argon-Oxygen and 100% Oxygen Breathing Mixtures."

[31] Bennett, P. "Prevention in Rats of Narcosis Produced by Inert Gases at High Pressures."

[32] Friesen, R. (1992). "Oxygen Concentrators and the Practice of Anaesthesia."

[33] Abraini, J., et. al. "Gamma-aminobutyric Acid Neuropharmacological Investigations on Narcosis Produced by Nitrogen, Argon, or Nitrous Oxide."

[34] Shulagin, Y., et. al. "Effects of Argon on Oxygen Consumption in Humans During Physical Exercise Under Hypoxic Conditions."

demonstrated in an animal model of stroke.[35] These observations, which utilized high concentrations of argon delivered at normal or elevated pressure, appear to have limited, if any, implications regarding the health impact of breathing air on the F-22, which is not known to exceed 5 percent argon at normobaric pressure.

### B.6.5 Tricresyl Phosphates

Recent reports have suggested the possibility that tricresyl phosphates (TCPs) and related organophosphate compounds, sometimes used as additives (1-5% by weight) in aircraft hydraulic fluids and engine oils, may contaminate engine bleed air as a consequence of worn or faulty seals, and contribute to adverse health effects among pilots and flight crews.[36,37] Certain TCPs have been associated with peripheral neuropathy following high exposure in experimental animals and humans.[38,39,40] The capacity of TCPs to promptly induce central nervous system depression or related symptomatology following acute inhalation as a fine mist or aerosol has not been established. In addition, there is no indication that human inhalation of TCP at a dose capable of causing overt acute CNS manifestations could occur in the absence of subsequent peripheral neuropathy.

Recent studies have detected measurable quantities of TCPs in the cabin air of commercial[41] and military aircraft,[42] apparently as a result of contamination of engine bleed air. In the study conducted by investigators at Cranfield University in the United Kingdom, TCPs were detected in 25 of 100 test flights of commercial aircraft.[43] The maximum concentration was 37.7 micrograms per cubic meter ($\mu g/m^3$) (22.8 $\mu g/m^3$ triorthocresyl phosphate (TOCP) plus 14.9 $\mu g/m^3$ other TCP isomers), which occurred as a short term (5 minute) peak value during a climb at high throttle. This observation was an outlier—the 95$^{th}$ percentile for the total TCPs for the climb phases of all flights was 0.2 $\mu g/m^3$. No acute central nervous system symptoms were reported by flight crews who sustained these exposures, which were well below regulatory

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[35] Ryang, Y., et. al. "Neuroprotective Effects of Argon in an In Vivo Model of Transient Middle Cerebral Artery Occlusion in Rats."

[36] Crump, D., et.al. "Aircraft Cabin Air Sampling Study (Parts 1 and 2)."

[37] Harrison, R., et. al. "Exposure to Aircraft Bleed Air Contaminants Among Airline Workers: A Guide for Health Care Providers."

[38] Siegel, J., et. al. "Effects on Experimental Animals of Long-Term Continuous Inhalation of a Triaryl Phosphate Hydraulic Fluid."

[39] Freudenthal, R., et. al. "Subchronic Neurotoxicity of Oil Formulations Containing Either Tricresyl Phosphate or Tri-Orthocresyl Phosphate."

[40] Craig, P., & Barth, M. "Evaluation of the Hazards of Industrial Exposure to Tricresyl Phosphate: A Review and Interpretation of the Literature."

[41] Crump, D., et.al. "Aircraft Cabin Air Sampling Study (Parts 1 and 2)."

[42] DeNola, G., et. al. "Determination of Tricresyl Phosphate Air Contamination in Aircraft."

[43] Crump, D., et.al. "Aircraft Cabin Air Sampling Study (Parts 1 and 2)."

limits. In particular, the TOCP concentration did not exceed the OSHA PEL for TOCP of 100 μg/$m^3$ as an 8 hour time weighted average, or the United Kingdom short term exposure limit of 300 μg/$m^3$ over 15 minutes.[44] There was no apparent correlation between TCPs and total VOCs, which typically ranged between 0.5 to 2 ppm during flight segments. A recent study reported on TCP concentration in 78 air samples obtained on military aircraft with a history of engine bleed air contamination.[45] The airborne concentrations of TCP in the cockpit/flight revealed generally low concentrations of TCP (less than 5 μg/$m^3$) with the exception of two results (51.3 and 21.7 l μg/$m^3$), the highest of which was associated with an engine oil spill and overt smoke in the cockpit. Full-throttle ground testing of the cabin air of a propeller model aircraft during an active turbine oil leak associated with the odor of burned oil yielded a median TCP concentration of 5.5 μg/$m^3$ (range 3.6 – 5.9 μg/$m^3$), with no ortho-isomers detected.[46]

Sampling for TCPs in the F-22 was conducted in ground tests of cockpit air in incident aircraft in the fall of 2011 (40 samples), and with swabs from engine surfaces in contact with bleed air in incident and non-incident engines at Elmendorf AFB in the late spring of 2011 (12 samples), and in incident jets in the fall of 2011 (20 samples). No TCPs were detected in any of these samples. The limit of detection for the air samples (based on determinations utilizing mixed cellulose ester filter cassettes on F-22 jet #42) was approximately 8 μg/$m^3$ for TOCP and 40 μg/$m^3$ for other isomers of TCP. These negative findings, combined with the known features of TCP intoxication, indicate that aircrews were unlikely to have sustained exposure to TCP of sufficient magnitude to result in sudden acute CNS symptoms. The low concentrations of other hydrocarbons associated with hydraulic fluid or engine oil measured in the engine bleed air of the F-22 offers additional reassurance that any TCPs possibly present were likely to have existed at comparably low levels. A biomarker of human TOCP exposure, based on detection of phosphorylated butylcholinesterase in serum, is currently under development.[47] Its availability in the future might enable bio-monitoring for TOCP to supplement industrial hygiene measurements.

## B.7 Summary

In summary, based on analysis of available data, the AOG Study Panel concludes that trace levels of VOCs and other chemicals are commonly present in the breathing air supplied by the OBOGS used in the F-22. The origin of these contaminants in the breathing air can be traced to their presence in atmospheric air and to leaks of small quantities of jet fuel, oil, or hydraulic fluid into the ECS of the aircraft. In flight tests and ground tests, neither the level of any single chemical contaminant nor the sum of the concentrations of all the contaminants detected reached a concentration consistent with the CNS symptoms reported in recent incidents. In addition,

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[44] Ibid.

[45] DeNola, G., et. al. “Determination of Tricresyl Phosphate Air Contamination in Aircraft.”

[46] Solbu, K. “Airborne Organophosphates in the Aviation Industry: Sampling Development and Occupational Exposure Measurements (No. 1068).”

[47] Liyasova, M., et. al. “Exposure to Tri-o-cresyl Phosphate Detected in Jet Airplane Passengers.”

biological monitoring tests conducted on the blood and urine of incident pilots and ground personnel as well as test pilots were negative for exposure to hazardous levels of carbon monoxide or other toxic substances.

# Appendix C: F-22 Combined Test Force Aircraft Instrumentation and Test Activities

## C.1 Objective

This appendix summarizes the testing conducted at the F-22 Combined Test Force, Edwards Air Force Base, California, in support of the 2011 Safety Investigation Board research into the root cause of F-22 fleet hypoxia-like incidents that have occurred since 2008.

## C.2 Background

Initial Air Force Flight Test Center (AFFTC) testing was accomplished from January to April 2011 using instrumented United States Air Force F-22 (specific aircraft serial numbers 91-4007 and 91-4009).

In December 2010, the Air Force Materiel Command (AFMC) Director of Air, Space, and Information Operations (AFMC/A3) granted a limited waiver to conduct On-Board Oxygen Generating System (OBOGS) testing up to 60,000 feet above mean sea level (MSL), which was higher than the 25,000 foot MSL restriction in place at that time.

In January 2011, temperature and pressure data were collected from four sensors installed at multiple locations in the Environmental Control System (ECS) of the F-22. Testing was performed with limited instrumentation in pursuit of ECS performance data and was executed as ride-along testing with other test programs. System performance was as designed with no deficiencies detected.

In April 2011, an oxygen concentration sensor and three additional pressure sensors were added to existing temperature and pressure sensors in the ECS of the F-22. Dedicated testing was executed with two different OBOGS units during maneuvers selected to reflect profiles of previous F-22 hypoxia-like incidents. System performance was as designed with no deficiencies detected.

Follow-on OBOGS ground testing began in mid-July 2011 and flight testing began July 25, 2011, and is described below. A total of 10 ground test and 20 flight test missions were executed as part of follow-on testing from July-October 2011.

## C.3 Aircraft Instrumentation (July-October 2011 Testing)

Aircraft 91-4009 was extensively modified with instrumentation presented in Table C-1 (below), with emphasis on collecting data on potential breathing air contamination. Real-time contaminant measurement devices (ppbRAE) were used to record and display the time-stamped total volatile organic compound count. The aircraft data system was used to record data from the added ECS instrumentation. Telemetry was used for real-time monitoring of the aircraft data in the control room. Vacuum (summa) canisters were used to collect air samples from three locations: OBOGS input, air feeding the pilot's mask post Breathing Regulator Anti-G (BRAG) valve, and cockpit ambient environment. Desorption tubes (D-Tubes) were used to collect air

samples from these same three locations for post-flight detection of specific potential air contaminants. Figure C-1 below presents a diagram of the instrumentation installed.

| Sensor | Method | # | Real-Time Data | Post-Flight Data |
|---|---|---|---|---|
| ppbRAE | Detector | 3 | Total VOC + alarm (no CO) | Plot of total VOC vs. time |
| ECS Instrumentation | Sensors in ECS ducting/lines | 9 | Temperature, pressure, $PPO_2$ (telemetry) | Temperature, pressure, $PPO_2$ |
| D-Tubes | Collection via filtration | 6 | N/A | Aldehyde ppb |
| Aircraft SUMMA | Air sample capture | 3 | N/A | Amount of 97 VOCs + TICs |
| ***Abbreviations:***<br>CO: Carbon Monoxide<br>ppb: Parts per Billion<br>TIC: Toxic Industrial Compound | | | N/A: Not Applicable<br>PPO2: Partial Pressure of Oxygen<br>VOC: Volatile Organic Compound | |

*Table C-1. Aircraft Instrumentation Added for Investigation.*

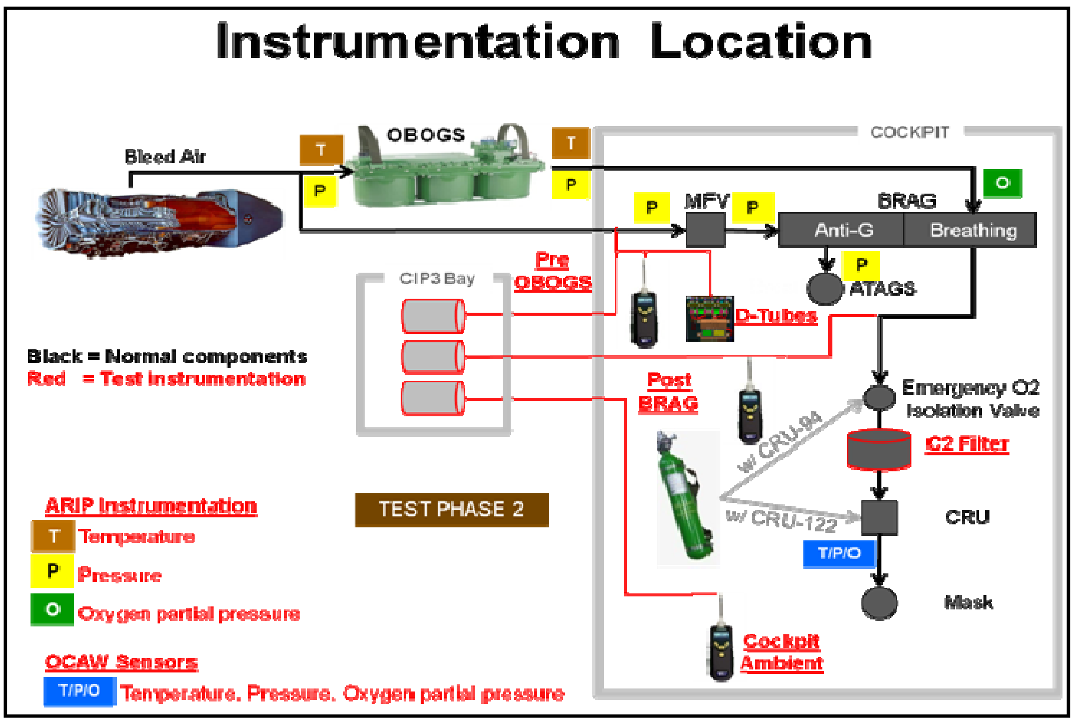


*Figure C-1. Aircraft Instrumentation Diagram.*

## C.4 Human Instrumentation

The oxygen caution and warning system (OCAW) was used for real-time oxygen partial pressure data collection and real-time warning to the pilot of low oxygen concentration. The OCAW sensor was mounted at the base of the pilot's mask hose and was developed for this specific application. The human measurements are listed in Table C-2 (below). Pilot-mounted instrumentation is shown in Figure C-2 (below).

| Sensor | Method | # | Real-Time Data | Post-Flight Data |
|---|---|---|---|---|
| Lung SUMMA | Air sample capture | 2 (pre/post mission) | N/A | Amount of 97 VOCs + TICs |
| OCAW | LED $O_2$ sensor | 1 | $PPO_2$ | $PPO_2$ |
| Filter | In development | 1 | N/A | In development |
| Chest Harness | Chest sensor | 1 | N/A | Heart data and respiratory rate |
| Pulse-Ox | Fingertip sensor | 1 | Blood $O_2$ saturation | Blood $O_2$ saturation |
| Blood Basic | Sample | 8-10 vials baseline & post | N/A | Standard blood data |
| Spirometry | Exhale | 2 (pre/post mission) | N/A | Lung function |
| Urine Tox | 24-hour collection | Baseline & post | N/A | Toxin presence |

***Abbreviations:***
LED: Light-Emitting Diode
OCAW: Oxygen Caution and Warning
Tox: Toxin, Toxicology
$O_2$, Ox: Oxygen
TIC: Toxic Industrial Chemical
VOC: Volatile Organic Compound

*Table C-2. Human Instrumentation.*

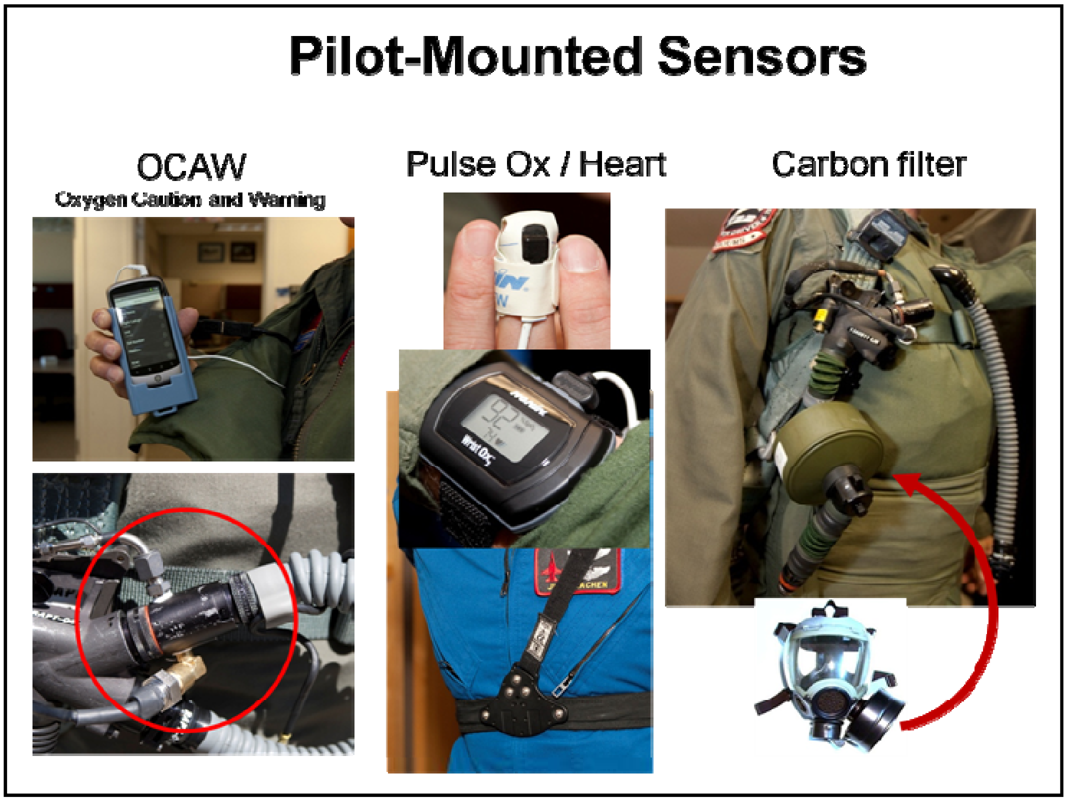


*Figure C-2. Pilot-Mounted Instrumentation.*

## C.5 Test Conditions (July-October 2011 Testing)

The flight test profiles and test points from test plan AFFTC-TP-11-30, *F-22 On-Board Oxygen Generating System Phase II Ground and Flight Test* are shown in Tables C-3 to C-5.

| Test Point | Altitude | A/S | Power | Load (G) | Comments |
|---|---|---|---|---|---|
| 1 | 10K ft MSL | 0.9M | As Req'd | As Req'd | a. Climb to 50K ft<br>b. Engine thrust request (ETR): Idle, bank and pull to 3 g's<br>c. Descend in idle to 45K ft |
| 2 | 10K ft MSL | 1.2M | As Req'd | As Req'd | a. Climb to 50K ft<br>b. ETR: Idle, bank and pull to 3 g's<br>c. Descend in idle to 45K ft |
| 3 | 55K ft MSL | 1.5M | As Req'd | As Req'd | a. Slow deceleration to 1M |
| ***Abbreviations:***<br>**A/S: Airspeed** **Ft: Feet**<br>**K: Thousand** **M: Mach** | | | | | |

*Table C-3. F-22 OBOGS Phase II Flight Test Profile A.*

| Test Point | Altitude | A/S | Power | Load (g) | Comments |
|---|---|---|---|---|---|
| 1 | 5K ft ± 500 ft MSL | 0.9 ± 0.05 M | MIL | As Req'd | a. Climb to 40K ft, maintain <50 AOC<br>b. MIL-IDLE snap at top of climb (1 minute of climb required)<br>c. End run at or below 100 KCAS |
| 2 | 18K ft ± 500 ft MSL | 430 ± 20 KCAS | As Req'd | As Req'd | a. Wind up turn (WUT) ____g (100% NzW), 120°-130° bank, continue turn through 90° of heading change<br>b. Continue turn, -10° to -20° gamma select AB, g as required to capture 300-350 KCAS through 270°<br>c. Wind-up turn ____g (100% NzW), full AB, pull to >36° alpha<br>d. Unload, -20 to-30° gamma, full AB to capture 300-350 KCAS<br>e. Repeat b, c, and d until 10,000 ft AGL |
| 3 | 18K ft ± 500 ft MSL | 430 ± 20 KCAS | As Req'd | As Req'd | a. Line abreast (LAB) @ set range +3K ft<br>b. Test will call for 45º check into chase<br>c. Test turns to lock chase and calls out range<br>d. Chase starts an easy turn into test and sets aspect<br>e. Test call decreasing range and "test is on" at set range<br>f. Floor: 5K ft AGL minimum, recommend 10K ft MSL<br>g. Control room monitor<br>h. Altitude – KIO if descend below floor<br>i. OBOGS<br>j. Traffic – KIO less than 5 nm (MSL = greater than floor – 1K ft but less than 25K ft)<br>k. Reset: (after KIO or Terminate)<br>l. Deconflict flight paths, then MIL power<br>m. Accelerate to 350 KCAS a start climb on ref heading<br>n. Chase move out to next set range +3K ft |
| 4 | 18K ft ± 500 ft MSL | 430 ± 20 KCAS | As Req'd | As Req'd | a. LAB 6-9K ft<br>b. Test will call for a 45° check away<br>c. Test will call "Turn in, test is on" at 3-5nm separation<br>d. Floor: 5K ft AGL minimum, recommend 10K ft MSL<br>e. Control room monitor<br>f. Altitude – KIO if descend below floor<br>g. OBOGS<br>h. Traffic – KIO less than 5 nm (MSL = greater than floor – 1K ft but less |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | than 25K ft)<br>i. Reset: (after KIO or Terminate)<br>j. Deconflict flight paths, then MIL power<br>k. Accelerate to 350 KCAS a start climb on ref heading<br>l. Chase move out to next set range +3K ft |
| 5 | As Req'd | As Req'd | As Req'd | As Req'd | a. MIL-IDLE-MIL throttle transients, optional |
| ***Abbreviations:***<br>AB: Afterburner<br>Alpha: Angle of Attack<br>Gamma: Flight Path Angle<br>KIO: Knock it Off<br>MIL: Military<br>nm: Nautical Mile | | | | | AGL: Above Ground Level<br>AOC: Angle of Climb<br>Knots Calibrated Air Speed<br>LAB: Line Abreast<br>MSL: Mean Sea Level<br>NzW: Load Factor Normal to the Flight Path |

*Table C-4. F-22 OBOGS Phase II Flight Test Profile E.*

| Test Point | Altitude | A/S | Power | Load (g) | Comments |
|---|---|---|---|---|---|
| 1 | 40K ft MSL to 5K ft AGL | As Req'd | As Req'd | 6 ± 2 | a. Setup at 40K ft, 25K ft, or 15K ft<br>b. Set mixture switch as appropriate (AUTO or MAX)<br>c. Ensure UPG is in appropriate configuration (connected or disconnected)<br>d. Sustained-g turn until 5K ft AGL is reached or sufficient data are collected<br>e. Repeat steps a-d as required |
| ***Abbreviations:***<br>UPG: Upper Pressure Garment | | | | | |

*Table C-5. F-22 OBOGS Phase II Flight Test Profile G.*

## C.6 Aircraft Configurations (July-October 2011 Testing)

Eight aircraft configurations were ground and flight tested from July to October 2011. The configurations included the incremental addition of components from incident aircraft in an effort to "stack the deck" against this test aircraft and induce conditions under which symptoms of root cause might be detected. Configuration 8 was used to investigate the phenomena of reduced oxygen output while under g that was evident in data collected in the earlier configurations. The configurations are listed in Table C-6 and the flight dates are listed in Table C-7 (below).

| Configuration | | Ground Test | ECS Stress: Profile A | Engine Stress: Profile E | G-Dip Inv: Profile G |
|---|---|---|---|---|---|
| 1 | Baseline (low performing OBOGS) | ✓ | ✓ | ✓ | |
| 2 | High-oil consumption engine from Elmo | ✓ | ✓ | ✓ | |
| 3 | Engine from an incident aircraft at Elmo | ✓ | ✓ | ✓ | |
| 4 | Engine from an incident aircraft at Elmo w/ collapsed scavenge tube | ✓ | ✓ | ✓ | |
| 5 | Engine from an incident aircraft at Elmo w/ collapsed scavenge tube and incident BRAG | ✓ | ✓ | ✓ | |
| 6 | Config 5 + high performing OBOGS | ✓ | ✓ | ✓ | |
| 7 | Config 6, Mixture Switch in AUTO | ✓ | ✓ | ✓ | |
| 8 | Installed: post-BRAG NeoFox & pressure sensors<br>Removed: incident engines, damaged scavenge tube, summas, RAEs | | ✓ | ✓ | ✓ |
| ***Abbreviations:***<br>Auto: Automatic<br>Elmo: Elmendorf Air Force Base | | Config: Configuration<br>w/: with | | | |

*Table C-6. Aircraft Configurations and Flight Profiles.*

| Config No. | Test/Test Configuration | Date Conducted |
|---|---|---|
| --- | Contaminate filter cockpit compatibility (ground test) | 7/13/2011 |
| | Contaminate filter cockpit compatibility test with boot & CRU-122 (ground test) | 8/26/2011 |
| 1 | Ground test | 7/16/2011 |
| | Ground test | 7/20/2011 |
| | Ground test | 7/29/2011 |
| | Flight profile A | 7/25/2011 |
| | Flight profile A | 7/30/2011 |
| | Flight profile E | 8/2/2011 |
| 2 | Ground test | 8/4/2011 |
| | Flight profile A | 8/5/2011 |
| | Flight Profile E | 8/9/2011 |
| 3 | Ground test | 8/10/2011 |
| | Flight profile A | 8/11/2011 |
| | Flight profile E | 8/12/2011 |
| 4 | Ground test | 8/15/2011 |
| | Flight profile A | 8/16/2011 |
| | Flight profile E | 8/17/2011 |
| 5 | Ground test | 8/23/2011 |
| | Flight profile A | 8/29/2011 |
| | Flight profile E | 8/31/2011 |
| 6 | Ground test | 9/1/2011 |
| | Flight profile A | 9/2/2011 |
| | Flight profile E | 9/8/2011 |
| 7 | Ground test | 9/8/2011 |
| | Flight profile A | 9/9/2011 |
| | Flight profile E | 9/13/2011 |
| 8 | Ground test | 10/18/2011 |
| | Flight profile A | 10/18/2011 |
| | Flight profile E | 10/19/2011 |
| | OBOGS set to MAX flight profile G | 10/20/2011 |
| | OBOGS set to AUTO flight profile G | 10/21/2011 |
| | OBOGS set to MAX flight profile G | 10/24/2011 |

*Table C-7. Ground and Flight Test Dates.*

## C.7 Results

There were no indications of failures of the aircraft life support components or contamination to the pilot's air supply.

# Appendix D:

# Human Systems Integration and the F-22's Environmental Control System (ECS) and Life Support System (LSS)

During the early Advanced Tactical Fighter (ATF) development program (the precursor of the F-22 program) Human System Integration (HSI) analysts were chartered to focus on Manpower, Personnel, Training, and Safety. From 1989 to 1994, analysts from the Aeronautical Systems Division (ASD) HSI Office were collocated to the ATF Program Office. As a consequence of a heightened awareness of the manpower, usability, maintainability, safety, human effectiveness, and cost savings achievable by the application of human factor engineering methods, the analysts and program leadership were able to bring about changes representing different priorities and policies in program management decision-making. Engineering, human factors, manpower, personnel, training, and logistics were integrated.

The HSI efforts within the ATF program focused on Air Force goals, including Air Force Specialty Code (AFSC) compression (5 AFSCs versus 15), reliability and maintainability objectives, reducing support equipment requirements, and reducing the logistics footprint. To achieve these goals, the analysts concentrated upon analysis of maintenance skills, reducing the required maintenance manpower, maintenance accessibility, the component maintenance concept, component self-diagnosis, trouble-shooting, training requirements, and improved engine performance, removal, and repair. As a result of their efforts, life cycle cost savings were estimated to be $780 million (M). Parts for the F-22 engine were reduced by 40%. Maintenance access to and around the ejection seat was improved. Support equipment was reduced by 75% less than legacy systems.[48]

Technical support of the efforts beyond the HSI technical capabilities embedded within the ATF System Program Office came from the Air Force laboratories and the ASD engineering offices in areas including: crew systems, life support systems, oxygen generation, propulsion, workload management, training methods and simulators, cockpit controls and displays, and human factors engineering. As a result of the ATF contract efforts, the F-22 pilot was given advanced personal protective equipment, integrated sensors, controls and displays, stealth technology, and sustained supersonic cruise.

At this same time, acquisition policies were changing, diminishing the influence of proven military standards as well as national and international standards. Additionally, the workforce was downsized in response to acquisition reform initiatives. During the early 1990s, the ASD HSI Office manning was reduced to 21 positions. In 1994, prior to the developmental flight tests of the F-22, the HSI program office was disbanded due to funding and personnel

[48] Carr, L. "F-22 HSI Case Study."

reductions within ASD and other Air Force organizations that had provided personnel positions. The expertise required to perform the critical integration analyses became insufficient.

Further atrophy of the then existing policies, and abandonment of military standards, occurred due to continued acquisition reform. In the period of 1999 to 2000, Air Force Research Laboratory (AFRL) personnel who had been supporting the development of performance standards, man-rating tests of the F-22 life support systems, and studies of altitude physiology, oxygen generation, and aviation occupational health and safety, including toxicology, were eliminated in a general AFRL reduction of funding and personnel. Note: See Appendix E of this report for details.

The F-22 program did not initially intend to create a life support system to raise the fighter's altitude capability, but rather to utilize the inherent altitude protection capabilities afforded by partial-pressure garments for G protection developed by Boeing under an Air Force advanced development program, the Tactical Life Support System (TLSS), that was initially used.[49] However, the F-22 life support system was designed to provide protection for high-altitude flight operations, in-flight decompressions, and high-altitude emergency escape to altitudes in excess of 50,000 feet to meet unprecedented gains in Soviet tactical air power.[50] The partial-pressure ensemble designed for the F-22 was viewed as "get-me-down" protection.[51] Its short duration capability is mandated by the 70 mmHg pressure breathing required (70 millimeters of mercury (mmHg), or about 1.3 pounds per square inch), which pushes blood peripherally, and slowly reduces cardiac output; this can cause dizziness and fainting. Thus, the G-suit is inflated to slow peripheral pooling and prevent these effects.[52]

From a total breathing air supply perspective that encompasses the ECS, as well as the life support equipment, some of the assumptions about the performance of the altitude protection system have proven to be based on incomplete data. For example, the understanding of the thermal management capacity of the F-22 aircraft ECS has proven to be limited. Excessive heat load from the mission avionics has caused the ECS to periodically shut down, resulting in disruption of the On-Board Aircraft Oxygen Generation System (OBOGS) inlet air from the ECS which in turn causes the oxygen generation system to shut down, thereby depriving the pilot of oxygen during those periods. Flight tests have been accomplished to define the causes and the duration of these ECS shutdowns.[53] These disruptions of the OBOGS inlet air flow may lead to the release of breathing air contaminates within the OBOGS molecular sieve due to relaxing the inlet pressure to 22 psig, as demonstrated for carbon monoxide.[54]

At the time of the F-22 LSS development, the knowledge of the ability of the OBOGS to filter or to pass contaminates was limited to likely flight line contaminates such as water, carbon

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[49] McGarvey-Buchwalder, D. "F-22 Life Support System for High Altitude Protection."

[50] Neubeck, G. "F-22 Concept of Operations above 50,000-ft."

[51] McGarvey-Buchwalder, D. "F-22 Life Support System for High Altitude Protection."

[52] Morgan, T. "BRAG Valve Overview."

[53] Javorsek, D., et. al. "F-22 All Weather Fighter: Recent ECS Testing Results."

[54] Gordge, D. "Transient CO Assessment."

dioxide, and carbon monoxide.[55] Organic and inorganic compounds were also explored by Ikels to develop general principles regarding the kinetic diameter of the molecules and their adsorption and desorption during the OBOGS pressure swing cycle, as well as their likelihood of finding their way through the crystal lattice of the zeolite bed into the breathing gas. At the time of this review, the database of molecules and compounds found in the F-22 ECS air that have been evaluated in terms of their ability to pass through the OBOGS into the breathing gas under various aircraft and OBOGS operating conditions has approached 300 molecules.

It was also presumed that at altitudes above 50,000 feet, the use of positive pressure breathing, maximum 93% oxygen rather than the 99+% oxygen, and the partial pressure suit created by a counter-pressure vest and extended coverage G-suit would be adequate to protect the pilot from decompression sickness and rapid loss of consciousness. The initial decision to raise the altitude limit to 60,000 feet was based upon extrapolation from United States Air Force and other air forces' altitude research experiments under conditions of rapid decompression to 50,000 feet. Tests conducted by the Air Force Armstrong Laboratory demonstrated that there was no statistical significance between oxygen concentrations of 99% during rapid cockpit decompression, which was the previous requirement, and oxygen concentrations from 93-95% to as low as 90% and 85% with dilution and non-dilution regulator settings, but the numbers of subjects were very limited.[56]

A second study that was conducted with one-second rapid decompressions (5 psi differential, or psid) to 46,000 feet, 52,000 feet, 56,000 feet, and 60,000 feet.[57] The Air Force TLSS ensemble was worn by the test volunteers. The TLSS demonstrated the effectiveness of the principle altitude and acceleration protection features of the crew-worn F-22 life support system. The TLSS provided: (1) a mask capable of sealing at high breathing pressure; (2) helmet assisted mask tensioning; (3) chest counter pressure equal to breathing pressure; (4) an extended coverage G-suit; (5) and a regulator capable of delivering breathing pressures for altitude up to 70 mmHg. Breathing pressures were 50 mmHg at 46,000 feet and 70 mmHg at each of the other altitudes. As with the original study, time at peak altitude was one minute, but the G-suit was inflated at peak altitude with positive pressure breathing. At least 13 exposures with male subjects were completed at each altitude.

With the improvements TLSS provided, the physiological measurements during rapid decompressions to 60,000 feet with 93% oxygen were better than those seen in the original study at 50,000 feet using 100% oxygen and the standard oxygen system. Additionally, subjects who had participated in both studies reported that, when wearing TLSS during a 60,000 feet decompression, the level of protection subjectively felt much better than using the standard oxygen system at 50,000 feet.

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[55] Ikels, K. "Effects of Contaminants on Molecular Sieve Oxygen Generators."

[56] O'Connor, R. "Use of Variable Oxygen Concentrations to 50,000 Feet."

[57] O'Connor, R., et. al. "Effect of Rapid Decompression to 60,000 Feet Using 94% Oxygen and Assisted Positive Pressure Breathing."

The actual maximum delivered oxygen concentration is a function of aircraft and cockpit altitudes, breathing load, ECS air characteristics, and OBOGS bay temperature, any of which can affect the concentration.[58]

To evaluate the performance of OBOGS in the F-22, as part of an investigation of operationally incurred hypoxia and hypoxia-like events, oxygen production tests were conducted to develop baseline data for the F-22 fleet.[59] One hundred twenty-five tests were conducted to measure oxygen concentration and OBOGS oxygen sensor error. Twenty retests were conducted to determine reproducibility of OBOGS performance. The tests were conducted at ground level with the OBOGS mixture switch set to MAX and the breathing rate was normal. One of the objectives of the tests was to identify OBOGS units that produced “outlier” performance. Note that OBOGS performance is improved at higher altitude, so these results may not be indicative of performance at reduced atmospheric pressures.

The results of these tests demonstrated that the operational fleet OBOGS units produced an average oxygen concentration of 85.1% with a standard deviation of 7.7%. The OBOGS internal oxygen concentration sensor errors, with respect to a reference instrument, averaged 0.5% from the reference, but the scatter of the measurements was large. The standard deviation was 10.9%. The threshold for a warning of oxygen generation failure was set at 10 psig to prevent a high probability of false F-22 ICAWS (Integrated Caution/Advisory/Warning System) alarms.

Man-rating tests of the OBOGS had been conducted by the Armstrong Laboratory in an altitude chamber at Brooks AFB at altitudes ranging from 10,000 feet up to 70,000 feet, unmanned at OBOGS inlet pressures of 35 and 80 psig.[60] Tests were performed in OBOGS AUTO and MAX modes. One test was conducted at an altitude of 10,000 feet with an OBOGS inlet pressure of 27 psig, outside the OBOGS operating specification for information gathering since lower pressures were not anticipated during normal ECS operations. Tests were then conducted with volunteer subjects wearing the contractor furnished F-22 LSS and also chemical-biological protection clothing configurations. The trials of the LSS consisted of breathing resistance evaluations, rapid decompressions, and tests of the Emergency Oxygen Supply (EOS) supply duration. Manned, one-second decompressions were completed over 5 psi differentials to final altitudes of 46,000 feet, 52,000 feet, 56,000 feet, and 60,000 feet. The OBOGS inlet pressures that were tested were 35 and 80 psig. The influence of lower OBOGS inlet pressures on oxygen concentration levels was not explored.

The current F-22 breathing system does not measure the oxygen concentration between the Breathing Regulator Anti-G valve and the pilot’s oxygen mask. An oxygen sensor has now been inserted in this position in an F-22 test aircraft, but the data are not available at the time of this writing. Other measurements were required, but the measurement techniques that have been

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[58] McGarvey-Buchwalder, D. “F-22 Life Support System for High Altitude Protection.”

[59] Hoog, S. “Safety Investigation Board OBOGS & Aircrew Flight Equipment to SAB Quick Look Study on Aircraft Oxygen Generation.”

[60] Diesel, D., et. al. “Human Performance Testing of the F-22 Life Support System.”

used have not proved to be completely adequate during the study. These measurements include key physiological state indicators, such as blood oxygen concentration and pulse rate, as well as accurate measurements of potentially hazardous air contaminates as a function of time. Measurement techniques used to detect contaminates have included swab samples taken at numerous aircraft and life support equipment surfaces and the use of summa canisters to sample air over varied time increments. These techniques are not capable of detecting short-duration, episodic releases of concentrated contaminates that might be released from the molecular sieve beds at low OBOGS inlet pressures. None of the tests measured periods of low OBOGS inlet pressure (other than during ECS shutdowns) that would have caused such episodic releases of contaminants.

The original standards applicable to the F-22 oxygen supply system were: Air Standard 61/101/1C, Minimal Protection for Aircrew Exposed to Altitude Above 50,000 Feet; Air Standard 61/101/6A, Minimum Physiological Requirements for Aircrew Demand Breathing Systems; and STANAG 3865, Physiological Requirements for Aircraft Molecular Sieve Oxygen Concentration Systems. To meet these requirements, the original F-22 LSS included a Backup Oxygen System (BOS) that would be activated automatically in event of oxygen supply failure to supply 93-95% oxygen to the pilot. The BOS was deleted from the LSS without integration of an automatic Emergency Oxygen System activation system as a result of a trade study.[61] The rationale for the elimination of the BOS and the recommended use of manual activation of the ejection seat mounted EOS Supply was described earlier in the Engineering Assessment section of this report.

Judging that the science and technology base was adequate for the areas of altitude physiology, altitude protection equipment, oxygen generation technology, high-altitude life support systems, and toxicology, a major reduction in AFRL science and technology personnel in these specialties was directed. This action was based upon the assumption that the existing technologies were adequate, understood, and could be accessed through a Defense Technical Information Center contractor analysis capability (i.e., the Human System Integration Information Analysis Center). The eventual loss of this Information Analysis Center services capability due to subsequent funding reductions deprived the USAF, other Services, and industry of the existing HSI tools, processes, lessons learned, and the foundation science and technologies for their application in the analysis of issues within other system acquisition programs, as well as diagnosis of human systems integration problems encountered during F-22 flight operations.

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[61] McGrady, M., & Holmdahl, M. "LSS OBOGS Standby Oxygen Trade Study (L-8935-92-MBM-013)."

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# Appendix E:

# Effect of Funding and Personnel Reductions: Human Performance Competencies

## E.1 Historical Background

In the decade following World War II, the method to store breathing oxygen as liquid oxygen was developed for fighter aircraft to replace gaseous oxygen stored in steel cylinders used throughout the war. Gaseous oxygen flowed from a liquid oxygen converter through a pressure demand regulator where the oxygen was usually diluted with cabin air. The United States (US) Air Forces developed a vast experience in the operational use and reliability of liquid oxygen storage, pressure demand regulators, and various aircrew masks. The weight and size advantage of liquid oxygen systems led to their use in nearly all high-performance combat aircraft.

However, liquid oxygen systems have significant disadvantages. The risk of contamination of the breathing oxygen by the inclusion of toxic compounds such as various oxides of nitrogen and carbon as well as hydrocarbons during manufacturing exists. Precautions must be taken to assure that moisture is excluded from the system to avoid the development of ice in the pipes and valves by the low temperatures generated by the expansion of gas when the oxygen flows within the system. Charging hoses and connectors must be purged with dry gas before use. Although the risk is very low, fuels, oils, fine particles of metal, and other materials that are combustible in 100% oxygen must be avoided in the charging components of both stored gas systems as well as liquid oxygen systems to prevent fire and explosion.[62]

Transferring liquid oxygen from its manufacturing plant to the aircraft liquid oxygen converter is an expensive process in terms of cost, ground equipment, and manpower. Only about 10 to 15% of the liquid produced by the plant reaches the aircraft oxygen converter. The rate of loss of oxygen from the converter, approximately 10% in 24 hours, makes recharging essential.[63]

The proven, though very low, risk of fires and explosions occurring in gaseous and liquid oxygen production plants, and during recharging aircraft oxygen as well as the need to separate re-arming and recharging of oxygen stores during rapid turn-around of aircraft in war have contributed to on-board oxygen generation becoming the method of choice for advanced high-performance combat aircraft.[64]

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[62] United States Department of Defense. “Design and Installation of Liquid Oxygen Systems in Aircraft, General Specification for (MIL-D-19326G).”

[63] Ernsting, J. “Conventional Aircraft Oxygen Systems.”

[64] Ibid.

The concept of on-board generation of breathing oxygen originated in the early 1960s as a result of the National Aeronautics and Space Administration's (NASA) interest in long duration space flight. There was a natural interest in this concept from the closed-cycle applications in spacecraft to semi-closed loop, and eventually, open loop applications in aircraft. The early investigations by the industry and the military air forces laboratories in the United States and the United Kingdom brought together multi-disciplinary teams of engineers, chemists, altitude physiologists, and aviation physicians. Oxygen generation technologies that were dependent upon a supply of air, and several that were air independent, were explored. Three systems, two air-supply dependent, advanced to the flight-test phase. By 1978, all were abandoned for various operating limitations with the exception of a pressure swing adsorption (PSA) concept.

The behavior of synthetic crystal zeolite and its performance in molecular sieves was well known. It could be tailored in terms of its structure, composition, and properties. In 1977, Litton offered a molecular sieve oxygen concentrator using zeolite capable of delivering 95% oxygen.

Prior to about 1976, an oxygen concentration of less than 99% would not have been sufficient. However, there was a successful demonstration of the protection of volunteer subjects wearing the advanced development Tactical Life Support System (TLSS) during rapid decompression at 60,000 feet.[65] The TLSS equipment provided assisted positive pressure breathing up to 70 millimeters of mercury.

After review of the results of research and advanced development efforts to provide oxygen generation using other chemical processes, the PSA molecular sieve process concept emerged as the clear choice. The PSA molecular sieve demonstrated the advantages of simplicity, small size, low weight and power requirement, minimal cost, and broad applicability to aircraft of crew sizes up to ten. Its principle disadvantage (i.e., producing less than 100% oxygen) can be overcome by the relatively simple expedient of adjusting the pressure delivery schedule of the breathing regulator, when this is required for hypoxia protection.[66]

Tests were conducted by the United States Air Force (USAF) School of Aerospace Medicine and at the Naval Air Development Center to characterize the performance of a two-person-capacity molecular sieve oxygen generation system under simulated flight conditions.[67] The US Navy conducted demonstration flight tests of the concentrator using the EA-6B aircraft, and then initiated the development of a system for the AV-8B aircraft for operational test and evaluation from 1977 to 1980.[68,69] The USAF modified the F-16 to incorporate on-board oxygen generation systems.[70]

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65 O'Connor, R., et.al. "Effect of Rapid Decompression to 60,000 Feet Using 94% Oxygen and Assisted Positive Pressure Breathing."

66 Miller, R., & Ernsting, J. "History of Onboard Generation of Oxygen."

67 Miller, R., et. al. "Molecular Sieve Generation of Aviator's Oxygen: Performance of a Prototype Under Simulated Flight Conditions."

68 Manatt, S. "Onboard Oxygen Generation Systems."

As a result of a briefing on the On-Board Aircraft Oxygen Generation System (OBOGS) advantages and flight test results, the Commander of the Air Force Systems Command issued a message in February 1983 to the Commander of the Aeronautical Systems Division stating:

> OBOGS has the potential to become the Air Force aviator's breathing gas system of the future. This system offers operational advantages, which should free the Air Force from dependence on liquid oxygen and its attendant logistics and safety constraints. It is time to step out with the OBOGS system.[71]

The Aeronautical Systems Division, as well as the US Army and US Navy, subsequently launched engineering development programs for molecular sieve oxygen generation systems for the air vehicles described earlier in this Aircraft Oxygen Generation Study Report.

## *E.2 The Science and Technology Base for Oxygen Generation Systems*

The knowledge and experience of the scientists and engineers of the Air Force, Army, and Navy Laboratories and Test Centers have been essential in the development, test, and evaluation of molecular sieve oxygen generation systems. However, these scientists and engineers have also recognized that there were sources of contaminates that could adversely affect the performance of the oxygen generator and the quality of the air provided to aviators. Examples include: contaminates in the ambient air such as exhaust from other aircraft, moisture that may accumulate in molecular sieve bed, toxic gases ingested by the engine during firing of munitions, or chemical/biological attack. Another example is the infiltration of aircraft lubricants, hydraulic fluids, and jet fuel into the engine bleed air, which then undergo pyrolysis and/or decomposition upon exposure to high temperature,[72] becoming potentially toxic and entering the cockpit and also the on-board oxygen generation system.

The extent to which such contaminates would be adsorbed on the molecular sieves depend greatly upon the polarity and dipole moment of the contaminate molecule, as well as its size, shape, and degree of unsaturation.[73] The molecular sieves currently used for separating nitrogen from oxygen have pore diameters of 4.2 Angstrom (type 5A molecular sieve) or 7.4 Angstrom (type 13X molecular sieve).[74]

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[69] Routzahn, R. "An Oxygen Enriched Air System for the AV-8A Harrier (NADC-81198-60)."

[70] Horch, T., et. al. "The F-16 Onboard Oxygen Generating System: Performance Evaluation and Man Rating (USAFSAM-TR-83-27)."

[71] Schroll, D., & McGarvey-Buchwalder, D. "Molecular Sieve On-Board Oxygen Generating System (OBOGS) Technical Assessment."

[72] Paciorek, K., et. al. "Fluid Contamination of Aircraft-Cabin Air and Breathing Oxygen (SAM-TR-79-34)."

[73] Ikels, K. "Effects of Contaminants on Molecular Sieve Oxygen Generators."

[74] Ikels, K., & Miller, G. "Molecular Sieves, Pressure Swing Absorption, and Oxygen Concentrators."

Extensive research was initiated within the Air Force Armstrong Laboratory to evaluate the effects of potential contaminates. These research efforts were focused on the effects of water, carbon dioxide, carbon monoxide, organic compounds, and inorganic compounds. Chemical warfare agent effects were studied in a joint United States – United Kingdom program as early as the 1980s.[75]

## E.3 The Search for Efficiencies within the Department of Defense Research Establishment

In the background of these research efforts, the Packard Commission's Blue Ribbon Panel was studying means to operate the Department of Defense (DoD) in a more efficient and economical manner. In June 1986, the Packard Commission issued its final report, *A Quest for Excellence*, proposing sweeping reforms to improve efficiency. President Reagan then signed National Security Decision Directive 219, directing implementation of the major recommendations of the Packard Commission. The Goldwater-Nichols Department of Defense Reorganization Act was signed into law that same year.

Efforts were undertaken to consolidate some military laboratory research functions under initiatives such as the Armed Services Biomedical Research Evaluation and Management (ASBREM) committee. ASBREM joint service agreements were, within the next five to six years, effective in these efforts. Chemical and Biological Warfare and Defense research was consolidated under the Army as the lead service. Thermal Physiology and Blast Effects Research was consolidated under the auspices of the Army Soldier Systems Center, Natick, Massachusetts. Army Toxicology Research personnel and facilities and Biodynamic Research facilities were collocated with the Air Force Aeromedical Research Laboratory at Wright-Patterson Air Force Base (WPAFB) and the Naval Health Research Center Detachment already collocated at WPAFB. Air Force, Army, and Navy research efforts on the biological effects of directed energy were consolidated at Brooks AFB, Texas. The Crew Technology Division of the Air Force School of Aerospace Medicine at Brooks AFB took the lead in the area of high altitude physiology and oxygen generation technology.

In 1989, Congressional representatives complained that the Services were dragging their feet in supporting management reforms initiated by the Packard Commission and the Goldwater-Nichols Act. President Bush directed the Secretary of Defense to draft a plan to look at ways to improve management (with fewer employees) and organizational efficiency in DoD. The goal was to devise a strategy to implement sweeping reforms proposed in the Packard Commission's report. Later that year, the Secretary of Defense appointed special groups to develop research and development strategies.[76] The Office of the Secretary of Defense and the Services established Project Reliance in 1990. The objective of this initiative was to reduce duplication across the Services and improve coordination and integration.

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[75] Ikels, K. "Effects of Contaminants on Molecular Sieve Oxygen Generators."

[76] Defense Science Board. "Report of the Defense Science Board Task Force on Research and Development Strategy for the 1990s (1990 Summer Study Volume 1, Executive Summary)."

In that same year, thirteen of the Air Force research laboratories were merged into four (the Armstrong, Phillips, Rome, and Wright Laboratories). The Armstrong Laboratory was formed from the laboratories and the USAF School of Aerospace Medicine that reported to the Human Systems Division. The Navy consolidated its technical infrastructure into four Warfare Centers. In 1991, the DoD-initiated, congressionally approved, Base Realignment and Closure (BRAC) actions led to the disestablishment and consolidation of management of nine Army laboratories under one command, and leading to the creation of the Army Research Laboratory. Similarly, the 1993 BRAC and the 1995 BRAC disestablished and transferred functions of the US Army's Fort Belvoir Research and Development Center and the Aviation Troop Command.

In order to provide a long-term vision for the Air Force research laboratories, the Air Force Scientific Advisory Board initiated a study.[77] The study, entitled *New World Vistas*, identified examples of Core Technologies, which did not include human systems or human performance technologies. Critical Technologies for the future were identified, but only the technology of Modeling/Simulation/Training intersected the human systems/performance domain. A six-point strategy for research and development investment was recommended. The highest priority recommended was the development of Breakthrough Technology from investments in Research (6.1), Exploratory Development (6.2), and Independent Research and Development. Specific budget recommendations with offsetting reductions were also recommended, some presuming that industry would carry on research and development where the investments by the government laboratories were eliminated or reduced.

In 1996, the National Defense Authorization Act directed the DoD to develop a 5-year plan and to set forth specific actions needed to "consolidate the laboratories and test and evaluation centers." The Secretary of Defense was to submit an initial plan to Congress no later than May 1996.

A single plan called Vision 21 was developed.[78] The plan identified three key pillars in accomplishing the desired laboratory reform. These were:

- Reduction of infrastructure costs with emphasis on high-maintenance and inefficient facilities while retaining critical capabilities.
- Restructuring resulting from improved processes and cross-service reliance.
- Revitalization of key laboratories with an emphasis on critical technologies.

Vision 21 played an important role in the Air Force's decision to continue to overhaul its laboratory infrastructure. The Air Force initiated a plan to reconfigure and streamline its laboratory structure to produce a more integrated and cost-effective operation. This action ultimately led to the decision in 1996 to reorganize and consolidate Air Force research resources

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[77] United States Air Force Scientific Advisory Board. "New World Vistas: Air and Space Power for the 21st Century – Summary Volume."

[78] United States Department of Defense. "Vision 21: The Plan for 21st Century Laboratories and Test and Evaluation Centers of the Department of Defense - Report to the President and Congress."

by establishing a single laboratory, the Air Force Research Laboratory (AFRL).

AFRL was activated in 1997.[79] AFRL was organized into the following technology directorates: Air Vehicles, Space Vehicles, Information, Munitions, Directed Energy, Materials and Manufacturing, Sensors, Propulsion, and Human Effectiveness. The Air Force Office of Scientific Research, which supports research in academia as well as within the AFRL technology directorates, also reported to AFRL.

## E.4 Air Force Research Laboratory Major Funding and Personnel Reductions

| | FY99 | FY00 | FY01 | FY02 | FY03 |
|---|---|---|---|---|---|
| **FY98 PB** | **$1,264** | **$1,312** | **$1,378** | **$1,412** | **$1,457** |
| **FY99 APOM** | **$1,012** | **$1,012** | **$1,085** | **$1,108** | **$1,132** |
| **Delta** | **-$252** | **-$300** | **-$293** | **-$304** | **-$325** |

*Table E-1. USAF Science and Technology Budgets for Fiscal Years (FY) 1999-2003. Note: Dollars in millions ($M)*

The creation of AFRL was intended to create efficiencies by streamlining its organization and reducing the management and support staffs of the four laboratories. Funding savings were to be used to revitalize the laboratory and its highest priority programs. However, shortly after the Laboratory was established, additional large funding reductions compared to the FY98 President's Budget (PB) were levied upon AFRL in the FY99 Amended Program Objective Memorandum (APOM) Science &Technology (S&T) Budget as shown in Table E-1 above. Dollars are in millions.

The S&T funding that had been allocated to the Armstrong Laboratory was reduced from $136M in FY96 to $82M (a reduction of 39.7%) in FY99.

The following criteria were used in implementing the AFRL research and development program reductions:

- Eliminate or reduce selected activities.

[79] Chait, R. "Perspectives from Former Executives of the DOD Corporate Research Laboratories."

- Work all eliminations/reductions vertically within the S&T budget , i.e., reduce the (normally) temporally-sequenced Basic Research, Exploratory Development, and Advanced Development budgets.
- Criteria to be used:
  - Support of the Air Force "Global Engagement" strategy.
  - Uniqueness to the Air Force.
  - Science and Technology portfolio balance.
  - Maintenance of critical mass and quality of research personnel and facilities.
  - Effect on reimbursable (leveraged) funding.
- Include both the programs and people associated with the recommended budget cut areas.

The research and development program impacts that are pertinent to the subject of this Aircraft Oxygen Generation (AOG) Study were:

- Aircrew Physiology Research was eliminated.
  - High Altitude Protection research was to end.
  - Spatial Disorientation research was stopped.
  - Aircrew Fatigue research was eliminated.
- Aircraft Oxygen Research was eliminated.
  - The Multi-Mission advanced development program was canceled.
  - The cooperative program with NASA was terminated.
- The Air Force component of the Tri-Service Toxic Hazards program at Wright-Patterson AFB was initially eliminated.
  - Reprogramming funds within the Human Effectiveness Directorate restored the half of the Toxic Hazards program that addressed occupational toxicology versus environmental toxicology.
  - Army personnel were eventually withdrawn from the US Army toxicology unit collocated at Wright-Patterson AFB.
- S&T funding for the Aerospace Medical Research being conducted by the Aeromedical Directorate of the Armstrong Laboratory and the USAF School of Aerospace Medicine was eliminated.
  - Aircrew physical and medical standards development were stopped.

The Aeromedical Directorate of the Armstrong Laboratory and the USAF School of Aerospace Medicine, including 502 positions which were funded by the Defense Health Program, were transferred from AFRL to the Human Systems Center at Brooks AFB.

The Armstrong Laboratory organization was reduced from six directorates to one directorate, the Human Effectiveness Directorate. Twenty-nine divisions were reduced to six divisions and 26 branches.

Losses of personnel authorizations that resulted from the elimination or reduction of Science and Technology Programs and the removal of the Defense Health Program components from AFRL are shown in Figure D-1.

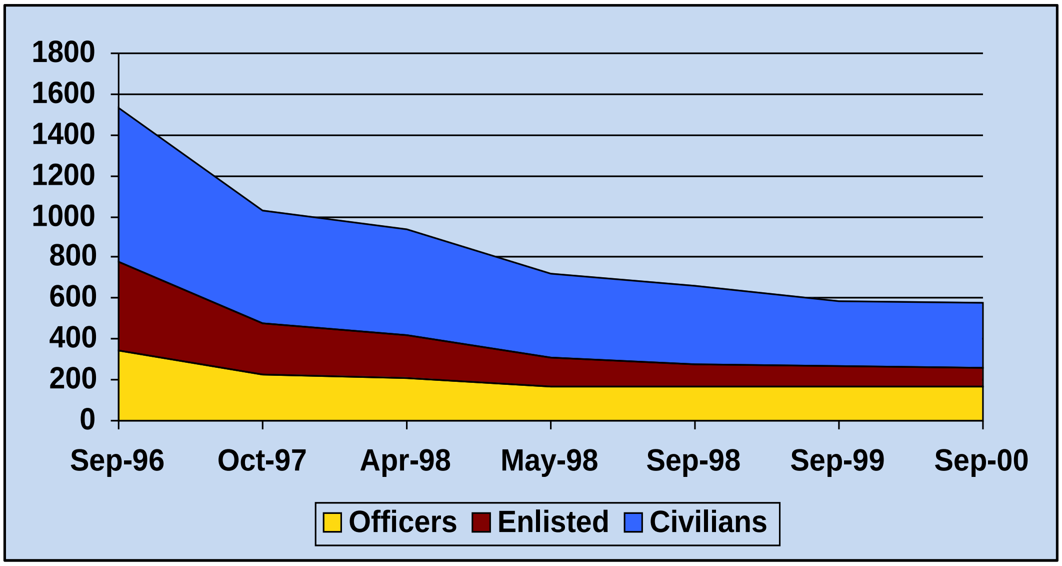


*Figure E-1. Losses of Military Officer, Enlisted, and Civilian Personnel Authorizations During the Period from September 1996 to September 2000.*

A reduction in the AFRL Human Effectiveness Directorate personnel amounting to 44% of the directorate's S&T workforce was accomplished over the period of FY99 through FY00.

There were many hard decisions made to accomplish the reductions to the Human Effectiveness Directorate. Additional factors influencing the decisions included:

- The Air Force was willing to accept a higher risk in the application of the human technologies.
- Aircraft cockpit design technologies, environmental protection research, and life support equipment, such as emergency escape systems, were considered mature and future research and development could be accomplished by industry.[80]
- The USAF Scientific Advisory Board had recommended that human augmentation technologies and human systems automation research were the highest priorities in order to reduce future Air Force personnel requirements.[81]

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[80] United States Air Force Scientific Advisory Board. "New World Vistas: Air and Space Power for the 21st Century – Summary Volume."

- Some of the human performance technologies were considered to be "soft sciences" where the return on investment was not easily quantified.
- Manpower and Personnel research was eliminated despite high quality scores from the Air Force Scientific Advisory Board—requirements and funding for the technologies by the Air Force using organizations were insufficient to support the envisioned benefits.
- Tri-Service research agreements were not protected from funding and personnel reductions.

## E.5 Human Performance Technologies Application

The application of the crew systems technologies, analysis tools, military standards, and design guidance developed by the Human Effectiveness Directorate hinges to a large extent upon the Air Force acquisition engineering organizations and, to a more focused extent, upon the practice of Human Systems Integration (HSI) within the Air Force and among Air Force weapon system contractors. Unfortunately, the function and benefits of HSI are not universally understood within the Air Force system acquisition community or its contractors. Its central role is frequently thought of as "human factors engineering."[82]

In the course of this AOG Study, the Panel was referred to Air Force Lieutenant Colonel Anthony Tvaryanas, a graduate of the Naval Post Graduate School with a doctorate degree in Human Systems Engineering, to define and clarify the importance of HSI in the development of weapon systems. As a result of our interview (A. Tvaryanas, personal communication, March 29, 2012), he briefly described HSI as:

> A systematic process for identifying, tracking, and resolving human-related issues ensuring a balanced development of both technologies and human aspects of complex systems. In order to ensure that all human-related issues are considered, the DoD categorizes them into several main areas or domains: human factors engineering, manpower, personnel, training, system safety, occupational health, personnel survivability, and habitability. A core principle of HSI is the necessity for those developing, acquiring, and operating systems to maintain a holistic perspective on these domains. No one domain should be considered in isolation—rather, they need to be related to each other as any decision in one domain can easily impact multiple other domains.
>
> HSI is dependent upon, and is executed through, a disciplined systems engineer process. In the absence of the latter, the former will be ineffective. Both

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[81] United States Air Force Scientific Advisory Board. "New World Vistas: Air and Space Power for the 21st Century – Summary Volume."

[82] Erickson, J., & Zacharias, G. "Report on Human-System Integration in Air Force Weapon Systems Development and Acquisition (SAB-TR-04-04)."

> processes seek to satisfy system stakeholders by incrementally growing system definition and development through a series of risk-driven decision milestones. Thus, they increase the likelihood of—but (importantly) cannot guarantee—project success.
>
> I will also emphasize the following specifically for the F-22 case: HSI is not synonymous with human factors engineering or environment, safety, and occupational health (ESOH), just as systems engineering is not synonymous with electrical or mechanical engineering. All are distinct disciplines, but HSI and systems engineering are unique in that they require breadth of knowledge (and perspective) over depth of knowledge. Thus, if one is looking for a deep understanding of the function of OBOGS, the HSI practitioner is not the appropriate POC [Point of Contact]—that would be the life support engineering and ESOH functions.

The first prototype Air Force HSI organization was created at the Aeronautical Systems Division (now the Aeronautical Systems Center) in 1981 in response to a report saying, "Effectiveness of US Forces can be increased through improved weapon system design," citing adequate Manpower, Personnel, and Training analyses as a shortfall. This finding was reinforced by similar findings by the Defense Science Board and then in 1985-86 by an Air Force Functional Management Inspection. This issue was further emphasized by Congressional action requiring manpower requirements to be submitted for systems at Acquisition Program Milestone I and II decision points. The Secretary of Defense directed that the topic be expanded to include Safety. The HSI organization was established at the Aeronautical Systems Center (ASC) as the prototype with the intention to place similar organizations at each product center if proven. Manpower and funding for the organization was provided by Air Training Command and Air Staff sources including: 15 from Air Training Command, 13 "Palace Acquire" positions from Air Force Deputy Chief of Staff for Personnel, four from Air Force Procurement, four from the Air Force Military Personnel Center, and two administrative positions from ASC.

The HSI program was successful in supporting the Advanced Tactical Fighter program, which was to develop the F-22 fighter. However, the HSI support to all ASC program offices was reduced and then eliminated by July 1994 due to Air Force-wide funding and personnel reductions occurring in the early 1990s.

The disestablishment of the prototype office occurred three years before the first flight test of the F-22 fighter. The HSI analysts had successfully addressed the integration of Manpower, Personnel, Training, and Safety aspects of Systems Engineering for the F-22. However, the HSI analysts did not have, nor were they intended to have, the technical skills to evaluate the adequacy of the pilot breathing system or the environmental control system. The Air Force engineering organization within the Aeronautical Systems Center and the Air Force Laboratories provided these skills (Personal Communication, D. McGarvey-Buchwalder, September 2011).

Efforts to reconstitute the HSI function in the late 1990s under the Human Systems Center were unsuccessful. In 2001, the commander of the USAF School of Aerospace Medicine asked the Air Force Surgeon General (AF/SG) to request the Air Force Scientific Advisory

Board (SAB) to study the requirement for Human Systems Integration. At the request of the Chief of Staff of the Air Force, the SAB then conducted a study.[83] The SAB reviewed current policies and practices (Air Force, DoD, and other Services) and collected inputs from key stakeholders to identify any shortfalls in current HSI practices. The SAB task also included assessment of the potential impact of HSI trends requiring change for the future and to recommend improvements in HSI policy, requirements, technology, and processes.

The SAB HSI Study final report concluded:

- HSI planning and execution on Air Force programs is hampered by lack of institutional support.
- Definitive, Air Force-wide policy and design guidance for HSI implementation is required.
- Senior-level organizational focus, oversight, and long-term advocacy must be provided.
- HSI education and training for program managers and acquisition professionals are required.
- Meaningful, quantifiable requirements for human performance must be developed.
- Required demonstrations of HSI effectiveness should be required at program milestones.

The SAB report states, "The Air Force should take steps to assure more effective collaboration between AFRL Human Effectiveness and Information Directorates and their counterparts at the Air Force product centers. AFRL should undertake focused S&T initiatives to address gaps identified in cognitive engineering, human behavior modeling, and system engineering tools." (Note: The Human Effectiveness Directorate had conducted human system engineering research, been responsible for the development of HSI tools, and supported the Human Systems Integration Information Analysis Center for all the Services.)

Furthermore, the SAB report indicated, "The Air Force should also request (in cooperation with the other services) DoD and Joint Services policy changes that will benefit all warfighters. These changes should include elevating crew systems to a higher level in DoD Work Breakdown Structure guidelines, incorporating HSI as an element of the DoD Architectural Framework, and expanding the Joint Services Specification Guide HSI provisions to address non-aircraft systems." This has not been accomplished within the Air Force, but it is at the discretion of the system program manager.

The AF/SG tasked his staff and 311th Human Systems Wing at Brooks AFB to develop a proposal for the Air Force HSI program. In 2006, the proposal was presented to the Air Staff and approved for implementation under the Air Force Vice Chief of Staff. The AF/SG agreed to fund the program for the first five years with line funding to be provided thereafter. A Joint

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[83] Erickson, J., & Zacharias, G. "Report on Human-System Integration in Air Force Weapon Systems Development and Acquisition (SAB-TR-04-04)."

Service HSI Steering Committee was also formed in 2006. The Air Force HSI program was expanded to encompass the technical domains of Manpower, Personnel, Training, Environment, Safety, Occupational Health, Survivability, Habitability, and Human Factors Engineering to mirror the HSI domains of the other Services.

Congressional direction was received for all Services to provide HSI reports. The Congress also directed Office of the Undersecretary of Defense (Acquisition, Technology, and Logistics) to take ownership of HSI in conjunction with its acquisition/systems engineering oversight role.

The USAF HSI Office then funded and placed HSI analysts at five Major Commands to assist in requirements and program analysis. AF Materiel Command (AFMC) established HSI strategic responsibility within the Systems Engineering Division (AFMC/ENS) of the AFMC Directorate of Engineering and Technical Management (AFMC/EN).

In 2008, the HSI organization, along with the USAF School of Aerospace Medicine at Brooks AFB, was transferred from the 311th Human Systems Wing to the 711th Human Performance Wing (HPW) of AFRL at Wright-Patterson AFB. The HSI analysts remained at Brooks AFB until 2011, when their 31 positions were transferred to the 711th HPW at WPAFB. Only two of the analysts moved to WPAFB, creating a major shortfall in HSI education, training, and experience.

An HSI Implementation Plan was approved by the AFMC Commander in 2011. However, the AF HSI Office and AFMC budget submissions were not approved under the line of the Air Force Program Objective Memorandum process. Although line funding is more appropriate for the HSI role in its engineering development role, the AF/SG agreed to continue funding the HSI organization at the 711th Human Performance Wing (31 positions) using Defense Health Program funding (contained within DoD Major Force Program 8) funding in consideration for its consultation role. Line funding for the AF HSI Office (two positions plus five contractors) has been promised for 2013.

## E.6 Summary

This Study found that the elimination of funding and personnel in the areas of altitude physiology, altitude protection, and oxygen generation systems research, and the reduction of occupational toxicology research have contributed to a significant reduction of the AFRL scientific and technical competencies required to diagnose, identify, and solve the life support system problems that exist in the F-22 fighter. The elimination of research on the influence of contaminates on the quality of the breathing gas produced by the OBOGS in its early stages has recently resulted in considerable time and expense to the F-22 program to expand the required technical knowledge. Ironically, at the time of the elimination of oxygen generation research, a PSA molecular sieve that incorporated a second carbon-based sieve was under development that would produce 99% oxygen and improve the filtering of contaminates by the OBOGS.[84]

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[84] Miller, G. "A 99% Purity Molecular Sieve Oxygen Generator."

After the abolishment of the first HSI office at ASC in 1994, the subsequent history of the Air Force HSI program illustrates the difficulty of completely reconstituting, and even expanding, the scope of a competency during periods of change in Air Force acquisition policies, budget considerations, closure of bases, and personnel reductions. The recent movement of the HSI organization, with the loss of the majority of the HSI practitioners, has resulted in the need to recruit and train a new workforce and to reestablish the benefits of HSI within system acquisition programs. Creating a robust HSI competency will be very difficult without more adequate and appropriately aligned funding (DoD Program 6 (specifically 6.4, Advanced Component Development and Prototypes) rather than Program 8), as well as strong institutional advocacy and priority.

Initial steps to reconstitute the appropriate competencies required to address the F-22 problem, as well as prevent potential problems in other existing or future aircraft programs, is currently underway by collaboration among and through:

- Components of the AFRL 711th Human Performance Wing (the Human Effectiveness Directorate, USAF School of Aerospace Medicine, and the Human Performance Integration Directorate),
- AFRL's Propulsion Directorate, Sensors Directorate, Materials and Manufacturing Directorate,
- Naval Medical Research Units technical support, and
- Technical consultation with NASA.

However, development of adequate research cadres, more capable sensors, test facilities, and modeling and simulation capabilities will require more personnel and funding resources than appear to this AOG Study Panel to be available at this time.

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# Appendix F: F-22 Program Schedule

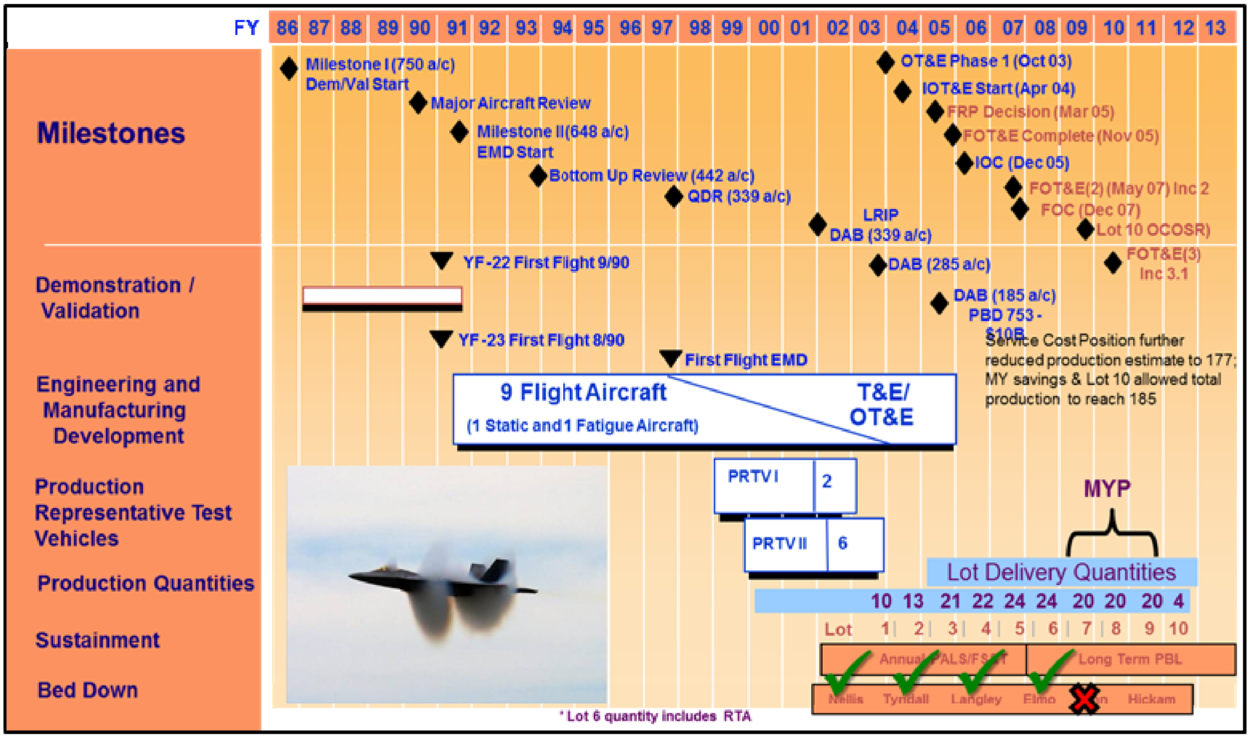


*Figure F-1. F-22 Raptor Program Schedule Showing Acquisition Milestones and Phases, Major Program Events, and Aircraft Lot Deliveries from Fiscal Year (FY) 1986-2013.*

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# Appendix G:
# Policies, Plans, and Procedures: Interviewees

| Date | Name & Position | Subjects Covered |
|---|---|---|
| 1 July 2011 | Mr. Robert Kuhnen<br>Air Force Materiel Command Standardization Officer<br>Former Chief of Aeronautical Systems Center (ASC) and Air Force Research Laboratory Engineering Standards Office.<br><br>Mr. Timothy Jennewine<br>Technical Director, Flight Systems Engineering Division<br>ASC Engineering Directorate<br><br>Mrs. Dawn McGarvey-Buchwalder<br>Technical Advisor for Airworthiness, ASC Systems Integration Office<br>Former F-35 Pilot Systems Program Lead<br>Former F-22 Life Support Systems Manager | Broad history of F-22 & On-Board Oxygen Generation Systems (OBOGS) |
| Jun 2011-Jan 2012 | Mr. Anthony Keen<br>F-22 Chief Engineer<br>Former F-22 Technical Director | |
| 19 July 2011 | Lt Gen Mark Shackleford, USAF<br>SAF/AQ Military Deputy<br>Former F-22 System Program Office (SPO) Director | Impacts of acquisition reform; Military Specification / Military Standard (Mil-Spec/Mil-Std) changes; Risk assessment process |
| 27 July 2011 | Lt Gen Robert Raggio (USAF ret)<br>Former F-22 SPO Director | Weight reduction Integrated Product Team (IPT) process; Mil-Spec/Mil-Std changes |
| 27 July 2011 | Mrs. Dawn McGarvey-Buchwalder | Safety Significant/Critical process; IPT process; Failure Mode Effects Criticality Analysis (FMECA) process |
| 28 July 2011 | Mr. Larry Carr<br>Former Chief, Human Systems Integration (HSI) CONOPS, Headquarters USAF | Evolution of HSI in the Air Force & F-22 |

| | | |
|---|---|---|
| 8 Aug 2011 | Mr. Jon Ogg<br>Former F-22 Chief Engineer | FMECA; Hazard analysis; Impact of erosion of Mil-Spec/Mil-Std; ASC & F-22 systems engineering capability |
| 8 Aug 2011 | Mr. Eric Abell<br>Former F-22 Chief Engineer | Weight reduction exercise; F-119 engine robustness; Mil-Spec/Mil-Std |
| 8 Aug 2011 | Mr. Chris Burke<br>Former F-22 Chief Engineer | FMECA; Atrophy of Systems Engineering Capability; Safety Significant/Critical process; Need for development planning organizations |
| 12 Aug 2011 | Mr. Ronald Dubbs<br>Former F-22 Chief Engineer | Weight reduction exercise; Change in responsibility for Mil-Spec/Mil-Std; Impact of Congressionally mandated budget cuts |
| 12 Aug 2011 | Brig Gen William Jabour, USAF (Ret)<br>Former F-22 SPO Director | Mil-Spec/Mil-Std; Weight reduction (Key Performance Parameter satisfaction) testing |
| 12 Aug 2011 | Mr. Douglas Ebersole<br>F-35 Director of Engineering<br>Former F-22 Chief Engineer | Environment Control Systems testing; Change management process; Navy vs. USAF Systems Engineering Processes |
| 12 Aug 2011 | Mr. Kevin Burns<br>Former F-22 Chief Engineer | Decision to remove Back-up Oxygen System; Evolution of Life Support IPT |
| 30 Aug 2011 | Mr. Michael Beauchamp<br>Former Director of F-22 Air Vehicle | Flight testing; F-22 Users Group; Lack of OBOGS end-to-end testing |
| 30 Aug 2011 | Lt Gen C.D. Moore, USAF<br>Former F-35 Deputy SPO Director<br>Former F-22 SPO Director | Impacts of acquisition reform; Navy vs. USAF functional capability; Implications of capability-based requirements; HSI implementation |
| 31 Aug 2011 | Mr. Mark Fraker<br>Former F-22 Chief Engineer | Operational Test & Evaluation; Impacts of acquisition reform; Independent air worthiness home office; HSI progress |

| | | |
|---|---|---|
| 1 Sep 2011 | Lt Gen James Fain, USAF (Ret)<br>Former F-22 SPO Director | Review early days of F-22 program; Impacts of acquisition reform; IPT development |
| 26 Sep 2011 | Lt Gen Thomas Owen, USAF<br>Commander, Aeronautical Systems Center<br>Former F-22 SPO Director | Mil-Spec/Mil-Std; Impact of manpower reductions; Acquisition Improvement Program; Risk assessment and evolution of HSI |
| 26 Sep 2011 | VADM Admiral David Architzel, USN<br>Commander, Naval Air Systems Command<br>Dr. Allan Somoroff<br>Deputy Commander, Naval Air Systems Command | Navy vs. USAF differences in implementing Goldwater-Nichols; Functional (home office) approach to acquisition oversight; Mil-Spec/Mil-Std; Inherently governmental functions |
| 10 Oct 2011 | Mrs. Dawn McGarvey-Buchwalder | IPT; Weight reduction exercise; Life Support System Trade Study |
| Nov 2011 | Mr. George Miller<br>711 Human Performance Wing/RHCP | Several discussions on multi-national air quality specifications and standards; Status of new USAF Air Standard Directive |
| Jun 2011 – Dec 2011 | Col Sean Frisbee, USAF<br>F-22 SPO Director | Continual dialogue on program history and performance |

*Table G-1. Scientific Advisory Board Aircraft Oxygen Generation Study Panel Interviewees. Note: The above individuals were interviewed with regard to various general or F-22 program-specific policies, plans, and procedures that did or might have contributed to the various F-22 OBOGS issues or to the Panel's understanding of the background of the F-22 program in general and the OBOGS in particular.*

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# Appendix H:
# Study Hypotheses and Questions Examined

A large number of potential hypotheses and sub-hypotheses were developed by the Aircraft Oxygen Generation (AOG) Panel in the course of its study efforts. As they were developed and refined, each was analyzed and responses provided by a technical team led by the F-22 System Program Office (SPO). As the AOG Study effort evolved and more data was received so did the list of hypotheses also evolve. The final hypotheses / sub-hypotheses / questions and the originally provided detailed discussion/response for each, as prepared and presented by the technical team led by the F-22 SPO, are set forth below. The responses of the technical team are provided in blue for clarity. Explanatory comments added after the hypotheses were developed and/or the response was presented to the AF Scientific Advisory Board (SAB) AOG Panel are provided as needed for clarity and are indicated by brackets [ ].

## *H.1 Hypothesis Category #1:*

## *The F-22 oxygen delivery system is failing to deliver adequate Oxygen ($O_2$) to the pilot, resulting in hypoxia symptoms that threaten flight safety.*

### H.1.1 Hypothesis 1A:

**The F-22 OBOGS [On-Board Oxygen Generation System] unit can episodically expel the contents of the zeolite sieve in such a way that trapped nitrogen, or other gases normally resident in ambient air, are passed into the breathing air, thereby reducing delivered oxygen to levels that threaten flight safety.**

***Response:* *Testing of OBOGS units at Patuxent River [Naval Air Warfare Center, Patuxent River Naval Air Station, Maryland] indicated with pressure transients at the inlet to the OBOGS, and particularly when the pressure was reduced rapidly even though it remained above the minimum acceptable pressure, could cause CO [Carbon Monoxide] molecules normally purged overboard to be expelled into the breathing air.***

***Question 1A-1.*** What are the likely conditions that might cause the F-22 OBOGS to episodically expel nitrogen or other gases normally found in ambient air into the breathing air that would result in reduced oxygen delivery to the pilot?

***Response:*** *Constituents that will affect $O_2$ content are nitrogen and water. Nitrogen would temporarily affect $O_2$ whereas liquid water permanently compromises concentrating capability. Pressure transients in OBOGS supply air were suspected of causing an $N_2$ release and test results were provided in the SAB brief, and are discussed above An aircraft startup transient or malfunctioning ECS [Environmental Control System] component could allow liquid water into the OBOGS; however, degraded $O_2$ performance and associated weight gain on returned OBOGS suggests liquid water has not been an issue on the F-22.*

***Question 1A-2.*** Are there conditions whereby such an event could occur and the ICAW [F-22's Integrated Caution, Advisory, and Warning] system not warn the pilot of such an occurrence?

***Response:*** *Assuming a properly operating OBOGS $O_2$ sensor and an accurate cockpit altitude signal to OBOGS, low $O_2$ due to nitrogen that persists for at least 12 seconds will result in an OBOGS FAIL to the pilot due to low $PPO_2$ [Partial Pressure of Oxygen]. A degraded OBOGS due to water contamination will similarly result in the same ICAW for the same reason. On the other hand, should the OBOGS be in the Auto Mode and the cockpit altitude signal to the OBOGS computer fail, the OBOGS could produce a significantly lower $PPO_2$ than desired and not illuminate the OBOGS Fail ICAW.*

***Question 1A-3.*** Could these phenomena increase the relative percentages of nitrogen and/or reduce the necessary levels of oxygen in the breathing air?

***Response:*** *Yes, although testing has yet failed to replicate an $N_2$ [Nitrogen] expulsion coupled with a corresponding reduction in $PPO_2$ that might cause hypoxia. Further, incident aircraft OBOGS inspections do not show weight gain nor degraded performance due to liquid water contamination.*

***Question 1A-4.*** Should a pilot ingest a greater percentage of nitrogen than desired for a given cockpit altitude, could that pilot experience symptoms similar to those associated with decompression sickness?

***Response:*** *Although it is possible that a saturation of nitrogen in the blood at altitude could cause decompression sickness, aggressive functional testing and the software deep dive of the OBOGS system makes such an occurrence highly unlikely.*

### H.1.2 Hypothesis 1B:

**A low inlet pressure to the OBOGS unit could result in a lower percentage of oxygen in the breathing air, reducing delivered oxygen to levels that threaten flight safety.**

***Response: The OBOGS works on the principle of Pressure Swing Adsorption and therefore system performance would be degraded by low inlet pressure. This possibility was evaluated on flight test aircraft. An ECS shutdown will produce a shutdown of the OBOGS.***

***Question 1B-1.*** What are the conditions that could cause a low inlet pressure to the OBOGS unit?

***Response:*** *ECS cutback, ECS shutdown or a Bleed Air Valve Failure will cause the ECS to reduce the pressure to the inlet of the OBOGS in such a way that the pilot may not receive the required amount of $O_2$. These are known modes and the dash one describes these situations along with the appropriate and corresponding actions to be taken by the pilot. Further, certain throttle transients could result in lower inlet pressure to the OBOGS. A throttle transient from Mil [Military] Power to Idle results in a drop in pressure to approximately 27 psi [pounds per square inch] in flight. A review of the flight test data and incident aircraft data shows the input pressure to OBOGS drops below the OBOGS regulation pressure only during ECS shutdown events.*

***Question 1B-2.*** Could such a condition occur for a period of time long enough to affect the quality or quantity of the breathing air and not cause the illumination of an ICAW light?

***Response:*** *Referring to the flight test and incident data, the ECS shutdowns are a short duration event (approximately 20-25 seconds). Every occasion of an ECS shutdown resulted in an ICAW alert to the pilot. In the event of a low inlet pressure to the OBOGS (below OBOGS regulation) that results in low OBOGS outlet pressure which drops below 10 psi a "Low Pressure" fault is set.*

***Question 1B-3.*** Could such an event also cause a change in the cockpit pressurization?

***Response:*** *Cockpit pressure is unaffected by throttle transients. The cockpit pressure is maintained by the cockpit pressure regulator and check valves in the system. If the ECS supply pressure is reduced due to an ECS shutdown eventually the cockpit pressure will slowly decay. Note: the cockpit pressure vessel is leak tested when the aircraft is delivered and every time a canopy is replaced.*

***Question 1B-4.*** Would there be any other indications to the pilot of such a situation?

***Response:*** *The onset of an ECS shutdown is preceded by a "quiet" cockpit. When the ECS shutdown occurs, the pilot receives the ECS Fail ICAW.*

### H.1.3 Hypothesis 1C:

**The OBOGS, Breathing Regulator Anti-G [BRAG] valve (possibly related to Multi-Function Valve interface conditions), or low pressure LSS [Life Support System] components downstream of the BRAG Valve may have a failure mode that allows a low oxygen condition to exist, reducing delivered oxygen to levels that threaten flight safety.**

***Response:* *A failure of the BRAG valve or the low pressure components between the valve and the pilot's mask could result in a failure to deliver adequate $O_2$ under pressure to the pilot. The addition of the $O_2$ sensor at the pilot's mask will provide further mitigation of these possible failures.***

***Question 1C-1.*** What failure modes could occur that could result in non-OBOGS filtered air getting into the breathing air?

***Response:*** *A path between inlet and product gas in the OBOGS, a path between the anti-G and breathing air paths in the BRAG valve, or a gross leak or break in lines such that system pressures/flows (approximately 2 in $H_2O$ [two inches of water pressure] downstream of BRAG, and approximately 30 psig [pounds per square inch gauge] between OBOGS and BRAG) can't keep up with the leak. Planned system integration testing (January 2012) will quantify how much of a leak can cause this issue and if existing aircraft faults and maintenance/pilot checks are adequate to find the leak.*

***Question 1C-2.*** What indications would the pilot have to indicate the presence of non-OBOGS air in the breathing air?

***Response:*** *Leaks downstream of OBOGS will result in an OBOGS FAIL due to low $PPO_2$ because of excessive product flow thru the OBOGS. A leak between the air paths in the BRAG valve would not be detectible but will become known to the pilot with the installation of the $O_2$ sensor.*

***Question 1C-3.*** Should such a condition occur, under what circumstances would the external air have too little oxygen (too high a concentration of other $O_2$ displacing gases) to result in hypoxic symptoms?

***Response:*** *At cockpit altitudes above 10,000 feet and depending upon pilot conditioning and exertion levels, the pilot could be in an environment whereby the $PPO_2$ might result in onset of hypoxia symptoms.*

### H.1.4 Hypothesis 1D:

**There may exist a leak or a failure mode in the air delivery path from the Main Engine Primary Regulator bleed air valves to the pilot's mask that reduces delivered oxygen to levels that threaten flight safety.**

***Response:* *These failures were highlighted in the previous hypothesis. The addition of the $O_2$ sensor at the pilot's mask will provide further mitigation of these possible failures.***

***Question 1D-1.*** What total system checks are performed on the F-22's air delivery path from the Main Engine Primary Regulator bleed air valves to pilot mask valve to determine the integrity of the delivery conduit?

***Response:*** *As of April 2011, a Breathing System Integrity Test was added as a 30-day recurring inspection. Previously this was done only when replacing a BRAG valve. This test verifies there are no leaks in the BRAG valve or the hoses between the BRAG valve and pilot. In addition the pilot does a leak test prior to each flight by holding their breath and checking the Flow Blinker on the BRAG. If the Flow blinker turns white it is an indication of a leak between the BRAG and pilot. Also the "Press-to-Test" button on the BRAG is a rapid inflation of the G-suit and test of the positive pressure breathing system. A recurring plumbing leak test was added as a 180-day recurring inspection. Previously this test was only accomplished when replacing the OBOGS or associated tubing. This test verifies there are no leaks in the lines between the OBOGS and BRAG Valve. No recurring inspection occurs for ducting upstream of the OBOGS. The ECS system has bleed leak detection upstream from the engine and APU [Auxiliary Power Unit] bleed ports up to the primary heat exchanger. This upstream leak detection is there primarily to protect structure from damaging bleed air temperatures should a leak occur. There is also a leak check conducted once at startup on the warm air manifold. This check was added when TMM [Thermal Management Mode] was implemented. The need for the check was again to protect structure and other components from APU bleed temperature when TMM is activated. There are no additional leak checks of the system downstream. There is however monitoring of Avionics Cooling demands and OBOGS outlet pressure that result in ICAWs if sufficient pressures are not being provided. Due to the low bleed pressures during ground idle operation the system operates just barely above these ICAW limits. Therefore any degradation of supply pressure due to a leak should be picked up during ground operation. In the case of OBOGS the downstream pressure switch would also indicate if a leak upstream of OBOGS was sufficient to degrade OBOGS.*

***Question 1D-2.*** What indicators are available to monitor the performance of the delivery conduit?

***Response:*** *The flow blinker is an active monitor of flow in the system which the pilot can test at any time to verify there are no leaks. At any time on the ground or in flight, the pilot can depress the "TEST" switch on the Breathing Regulator Anti-G (BRAG) valve to provide higher pressure oxygen to the mask when the OBOGS is on. Depressing the TEST switch will also inflate the lower G-garment and upper pressure vest.*

***Question 1D-3.*** What is the inspection frequency for that conduit?

***Response:*** *See 1D-1 response. [Also] Prior to the SIB [Safety Investigation Board] investigation (January 2011), the Breathing System Integrity Test and plumbing leak test were only accomplished as a part of regression testing after maintenance that would require the removal/replacement of the BRAG valve or other components in the system that could result in a system leak. Post January 2011, these inspections were added as periodic.*

***Question 1D-4.*** Is there a failure mode where by a leak could cause a saturation of the OBOGS molecular sieve during normal inlet pressure periods and then when low inlet pressure occurs, allow inadequate levels of oxygen to be delivered to the pilot?

***Response:*** *Not certain of the potential for this failure mechanism. But if there was a downstream leak of the OBOGS coupled with the pilot's breathing that would exceed 200 liters/minute flow rate it could result in a low $PPO_2$ condition. A One Time Inspection (OTI) that performed both the Breathing System Integrity Test and plumbing leak test found approximately 10% of the [F-22] fleet with either a breathing hose that leaked or a leaking plumbing connection. The leaks were large enough to be detected by the testing but not large enough to cause an OBOGS FAIL ICAW for low $PPO_2$. Further testing is planned to evaluate the leak rate required to cause dilution at the pilot's mask.*

### H.1.5 Hypothesis 1E:

**The F-22 OBOGS unit's scheduled delivery of oxygen to the pilot can be late or impaired in its ability to perform satisfactorily based on climb rate, oxygen generation performance or a combination of its filter/purge and ambient pressure relationship to the algorithms scheduling its operation, reducing delivered oxygen to levels that threaten flight safety.**

***Response:* *While the system is designed to always provide adequate $O_2$ levels based upon cabin altitude, system performance could lag aircraft climb performance. CTF [F-22 Combined Test Force] test data is available that characterizes the delay in $O_2$ concentration increases to the pilot. Additionally the added $O_2$ sensor will provide pilot real time status on $O_2$ concentration adequacy.***

***Question 1E-1.*** What valves are scheduled by the ambient pressure and desired cockpit pressurization schedule that might fail or operate too slowly to ensure proper cockpit pressurization or the correct percentage of oxygen to the pilot?

***Response:*** *Three OBOGS charge/vent valves operate to change between 3 charge/vent ratios in auto mode to vary $O_2$ concentrating performance as needed for the cockpit altitude. The cockpit pressure regulating valve controls proper cockpit pressurization.*

### H.1.6 Hypotheses 1E-1:

**There may be a combination of conditions in the F-22's operating envelope whereby the F-22's Oxygen Delivery System does not deliver the desired percentage of oxygen to both the pilot and the breathing vest, which could result in hypoxia and threaten flight safety (e.g., sustained period of significant "G"-loading and/or during rapid descents with low power).**

***Question 1E-1a.*** Is the ability of the OBOGS to produce oxygen affected by the G-loading on the aircraft?

***Response:*** *Flight data does indicate the percentage of $O_2$ production is reduced during maneuvers where the aircraft experiences more than 6 Gs. That phenomenon was not observed when testing the OGOGS production capability in the centrifuge. Planned system integration testing with complete pilot ensemble will investigate/explain $O_2$ concentration G-Dip phenomenon.*

***Question 1E-1b.*** When the pilot and breathing vest demand a greater flow of breathing air, is the OBOGS unit able to produce the desired percentage of oxygen under all conditions?

***Response:*** *In-flight testing of the OBOGS $O_2$ production capability did not indicate a significant difference between the $O_2$ produced when using only the mask versus having both the mask and the breathing vest connected. Further, the percentage of $O_2$ produced did not vary significantly in either of the above situations while using either the MAX [Maximum] or AUTO modes.*

***Question 1E-1c.*** If the percentage of oxygen produced is less than desired, but greater than the "warning band" schedule, are there potential conditions (e.g., during a period of sustained "G-Loading" or physical exertion) whereby a pilot could experience the symptoms of hypoxia?

***Response:*** *Oxygen desaturations were not observed during CTF testing in conjunction with "G" maneuvering, although $O_2$ concentration G-Dip was observed. Production $O_2$ sensor will track OBOGS performance for comparison with Pulse-Ox [Pulse Oximeter] desaturations data.*

***Question 1E-1d.*** Are there conditions whereby the breathing rate of the pilot and the inflation rate and pressure of the breathing vest could result in short or long term effects to the pilot (e.g., Raptor Cough, CNS [Central Nervous System] symptoms, hypoxia)?

***Response:*** *No manned centrifuge testing is currently planned to explore this question although the recently formed physiology team is investigating potential causes of Raptor Cough.*

***Question 1E-2.*** What indications does the pilot have to indicate that either the cockpit pressure or the percentage of oxygen being delivered is too low?

***Response:*** *Cockpit pressure going outside expected pressure will result in an ICAW to the pilot. A low $O_2$ to the pilot will result in an OBOGS FAIL ICAW due to a low $PPO_2$ condition when $O_2$% [oxygen percentage] falls below the warning band. If cockpit*

*pressurization decays below the target set point a cockpit pressure ICAW will set if greater than 2.5 psi low. Additionally, Update 5 S/W [software] plans to incorporate changes to ensure robustness of cockpit altitude signal to OBOGS. Addition of production $O_2$ sensor will provide backup indication as to adequacy of $O_2$ concentration.*

### H.1.7 Hypothesis 1F:

**There may have been a component in the air delivery path from the APU or Main Engines' bleed air sources to the pilot mask valve that has been re-sourced to another vendor in the F-22 supply chain, and whose specifications have changed in a way that a different failure mode may be able to occur which reduce delivered oxygen to levels that threaten flight safety.**

***Response: No changes in suppliers or in system specifications were identified that occurred after system qualification. A major change in system design occurred during development when the Air Force directed the SPO to make use of existing AF [Air Force] Life Support equipment rather than to pursue the contractor furnished design and equipment.***

***Question 1F-1.*** Have there been changes in sub-level suppliers since 2007, either a new company or in the processes used by the original supplier, to produce parts and/or components to the F-22 Oxygen delivery system?

***Response:*** *Yes, although NFF [No Fault(s) Found] on returned LSS components (OBOGS and BRAG) plus no pattern on incident hardware serial numbers or manufacture date suggests no correlation with these changes and the incidents.*

***Question 1F-2.*** How have their products been tested and/or certified?

***Response:*** *Further investigation is needed to answer this question.*

***Question 1F-3.*** Are any of those components or parts on a critical path with regard to safety of flight?

***Response:*** *Further investigation is needed to determine the specific function of the changed parts in the OBOGS/BRAG with regards to the safety aspects of the components.*

## *H.2 Hypothesis Category #2:*

## *The F-22 oxygen delivery system is either ingesting or allowing a leakage of a toxic compound or compounds, which are not being filtered from the breathing air and thereby resulting in hypoxia-like symptoms that threaten flight safety.*

### H.2.1 Hypothesis 2A:

**The F-22 OBOGS unit can become saturated with undesirable agents, thereby reducing its effectiveness to filter out Nitrogen or other undesired contaminants (e.g., Argon, CO, VOCs [Volatile Organic Compounds], or other toxins), resulting in hypoxic-like symptoms that threaten flight safety.**

***Response:*** ***Saturation of the zeolite crystals with a contaminant could reduce the OBOGS performance. This potential was evaluated in laboratory tests which showed this to be unlikely without excessive levels of contaminants.***

***Question 2A-1.*** Could the undesired contaminants come from either the bleed air from the compressor or from a leak of another substance in any of the heat exchangers?

***Response:*** *Yes. There is a potential that contaminants could be introduced through the engine or heat exchangers. But thus far, we have been unable to detect any harmful substance at a level that might cause harm to the pilot.*

***Question 2A-2.*** What is the list of undesired contaminants that could be expelled into the breathing gas?

***Response:*** *Recommend using the Molecular Characterization Matrix as an attachment to address this.*

***Question 2A-3.*** Could the effectiveness of the purge cycle be affected by the differential between the OBOGS internal pressure and the external ambient pressure?

***Response:*** *The OBOGS is more efficient at higher altitudes due to the reduced ambient pressure. At the lower altitudes, with pressure transients at the OBOGS inlet, testing has shown an ability of the OBOGS to expel a greater volume of carbon monoxide into the breathing air.*

***Question 2A-4.*** What are the likely symptoms for a pilot who may have ingested those contaminants?

***Response:*** *Symptoms can vary from hypoxic-like to CNS disorders depending on contaminant and concentration. Refer to the discussion on the "Characterization of Chemicals on the F-22" in this report [Page 32 and also Appendix B].*

***Question 2A-5.*** How did the supplier for the F-22 OBOGS decide the input and output filter efficiency and micron size?

***Response:*** *Filter input was selected to protect immobilized zeolite beds from specified contamination while maintaining an acceptable pressure drop. Output filters were sized to*

*protect against the potential of failed zeolite bed material propagating downstream into the pilots mask. OBOGS Supplier is assessing improved filtration for outlet filter should a change be deemed necessary.*

***Question 2A-6.*** With other OBOGS systems using smaller micron size filters, what differences in ability to filter undesirable contaminants could be expected?

***Response:*** *Mechanical bed immobilization can allow some zeolite shifting and consequential dust generation. Smaller outlet filter size limits introduction of this dust into the product gas.*

### H.2.2 Hypothesis 2B:

**The F-22 OBOGS unit can episodically expel the contents of the zeolite sieve in such a way that trapped undesired contaminants are passed into the breathing air, resulting in hypoxic-like symptoms that threaten flight safety.**

***Response: A detailed response to characterize the extremely small quantities of VOCs released into the product gas under specific test conditions during Honeywell Des Plaines OBOGS challenge testing [e.g., testing done at Honeywell's facility located at Des Plaines, Illinois] will be provided as a set of charts. This chart deck will summarize all challenges conducted with associated test conditions and results.***

***Question 2B-1.*** What are the likely conditions that might cause the F-22 OBOGS to episodically expel undesired contaminants into the breathing air?

***Response:*** *Pressure transients to the OBOGS inlet supply or high humidity at OBOGS inlet air supply are suspect conditions based on NAVAIR [Naval Air System Center] and Des Plaines Testing.*

***Question 2B-2.*** Are there conditions where by such an event could occur and the ICAWS system not warn the pilot of such an occurrence?

***Response:*** *Yes, there are no aircraft warnings for VOCs, CO, or CO2 [Carbon Dioxide].*

***Question 2B-3.*** Could this phenomenon produce irritating or debilitating levels of undesired contaminants to be ingested by the pilot?

***Response:*** *This question is being addressed by the aviation medical community as part of the molecular characterization matrix efforts. Recently formed physiology team is investigating potential causes of Raptor Cough.*

### H.2.3 Hypothesis 2C:

**The OBOGS, Breathing Regulator Anti-G valve (possibly related to Multi-Function Valve interface conditions) or low pressure LSS components downstream of the BRAG Valve may have a failure mode that allows a contamination condition to exist, resulting in hypoxic-like symptoms that threaten flight safety.**

***Response:*** ***While none of these components were designed to eliminate potential contaminants, a leak downstream of the BRAG valve would allow cabin air to enter the system which is bleed air from the same source that feeds the OBOGS and assumed to be breathable.***

**Question 2C-1.** What failure modes could occur that could result in non-OBOGS filtered air getting into the breathing air?

***Response:*** *Same answer as 1C-1.*

**Question 2C-2.** What indications would the pilot have to indicate the presence of non-OBOGS air in the breathing air?

***Response:*** *Same answer as 1C-2.*

**Question 2C-3.** Should such a condition occur, under what circumstances would the external air either have too little oxygen or too many other contaminants such that hypoxia symptoms would result?

***Response:*** *VOCs introduced at a level that may cause pilot impairment will not immediately affect $O_2$ however prolonged VOC exposure has been shown to reduce bed concentrating efficiency which does drop $O_2$ concentration (>100 ppm [parts per million] over >10 hours reduced $O_2$ output from >90% to 79%). Hypoxia symptoms associated with VOCS are being addressed by the aviation medical community as part of the Molecular Characterization Matrix efforts.*

### H.2.4 Hypothesis 2D:

**There may exist a leak or a failure mode in the air delivery path from the Main Engine or APU bleed air sources to the pilot's mask that allows unfiltered contaminants to be delivered to the pilot, resulting in hypoxic-like symptoms that threaten flight safety.**

***Response:*** ***See 1D-1.***

**Question 2D-2.** What indicators are available to monitor the performance of the delivery conduit?

***Response:*** *See 1D-2.*

**Question 2D-3.** What is the inspection frequency for that conduit?

***Response:*** *See 1D-3.*

**Question 2D-4.** Is there a failure mode where by a leak could cause a saturation of the OBOGS molecular sieve during normal inlet pressure periods and then when low inlet pressure occurs, allow unacceptable levels of undesired contaminants to be delivered to the pilot?

***Response:*** *See 1D-4.*

### H.2.5 Hypothesis 2E:

**The F-22 OBOGS unit's scheduled delivery of Oxygen to the pilot can be late or impaired in its ability to perform satisfactorily based on climb rate, oxygen generation performance**

**or a combination of its filter/purge and ambient pressure relationship to the algorithms scheduling its operation, resulting in hypoxic-like symptoms that threaten flight safety.**

***Response:*** ***Addressed in flight test profiles and reported earlier.***

***Question 2E-1.*** What valves are scheduled by the ambient pressure and desired cockpit pressurization schedule that might fail or operate too slowly to ensure proper cockpit pressurization or the correct filter/purge rate to prevent undesirable contaminants from being delivered to the pilot?

***Response:*** *Three OBOGS charge/vent valves operate to change between 3 charge/vent ratios in auto mode to vary $O_2$ concentrating performance as needed for the cockpit altitude. The cockpit pressure regulating valve controls proper cockpit pressurization but will not affect contaminants in the cockpit.*

***Question 2E-2.*** What indications does the pilot have to indicate that either the cockpit pressure is too low or the OBOGS is not performing appropriately during the unprecedented changes in altitude created by the F-22?

***Response:*** *Same answer as 1E-2.*

### H.2.6 Hypothesis 2F:

**There may have been a component in the air delivery path from the Main Engines or APU bleed air sources to the pilot mask valve that has been re-sourced to another vendor in the F-22 supply chain, and whose specifications have changed in a way that a different failure mode may be able to occur which could result in a failure to eliminate an undesired contaminant before delivering breathing air to the pilot, resulting in hypoxic-like symptoms that threaten flight safety.**

***Response:*** ***No changes in suppliers or system specifications have been identified. Documented hardware failures failed to demonstrate introduction of contaminants into the system.***

***Question 2F-1.*** Have there been changes in sub-level suppliers since 2007, either a new company or in the processes used by the original supplier to produce parts and/or components to the F-22 Oxygen delivery system?

***Response:*** *Same answer as 1F-1, although since this hypothesis is about contaminant filtering, the relevant changes would be associated with the OBOGS inlet and outlet filters and the zeolite beds and there have been no changes in suppliers for these components. Zeolite beds were specifically looked at and the results of investigation were provided to Gen Hoog SIB [OBOGS and Aircrew Fight Equipment (F-22 Focus) Class E Safety Investigation Board chaired by then-Major General, now Lieutenant General Stephen L. Hoog, USAF].*

***Question 2F-2.*** How have their products been tested and/or certified?

***Response:*** *Further investigation is needed to answer this question.*

***<u>Question 2F-3.</u>*** Are any of those components or parts on a critical path with regard to safety of flight?

***<u>Response:</u>*** *Performance of these parts is critical to $O_2$ concentrating performance which is monitored and substandard performance is alarmed to the pilot via OBOGS FAIL ICAW. Although OBOGS does act as a filter for VOCs, the inlet air standards imposed on the Supplier do not require it to act as a VOC filter which is why a supplemental aircraft filter is being currently investigated.*

# Appendix I: Terms of Reference

## USAF Scientific Advisory Board
## Quicklook Study
## Aircraft Oxygen Generation

### Background

Many aircraft make use of an on-board oxygen generation system to provide breathing oxygen for the aircrew. Recently, there have been a number of hypoxic-related incidents that may be related to OBOGS or its installation. An investigation of system safety issues involving OBOGS is required to ensure that the appropriate steps are being taken to enhance flight safety of these aircraft.

### Charter

The Study will:

- Continue the evaluation of the F-22 oxygen ($O_2$) system to include developing the means to gather dynamic in-flight information to identify the root cause of reported hypoxia incidents.
    - Recommend refined peacetime altitude restrictions when greater data fidelity is available on OBOGS overall fleet wide performance.
    - Review current aircraft $O_2$ design and offer any changes, if required, for the F-22 configuration of OBOGS, BRAG valve, back-up $O_2$ supplies, automatic system activation, PVI design, and overall system inspection/self-test cycle.
- Evaluate OBOGS, and life support systems in general, to determine commonalities and acquisition philosophy across MDS and identify design limitations and/or key assumptions.
    - Review practice of "fly to warn" systems that may only allow the absolute minimum level of $O_2$ required in rapid decompression situations.
    - Make recommendations on the use of "automatic activation" backup $O_2$ with respect to normal aircraft operating altitude and agreed-upon aviator response time.
- Evaluate further investigation into contaminants that potentially impact OBOGS operation and follow-on performance effects on aircrew.
    - Ensure testing includes dynamic ECS-induced temperature heat/cooling cycle that may affect the chemical composition of various aircraft inlet-ingested contaminants.
    - Explore the development and fielding of filters or catalysts to negate the impact of the most likely contaminants found in OBOGS product gas when operating in common aviation environments (combat and peacetime).
- Direct and evaluate, if able, human response to high altitude, rapid cabin altitude changes, and rapid decompression environment with less than 90% supplied $O_2$.
    - If warranted, based on F-22 oxygen sensor data, direct evaluation of low $O_2$ (less than 21%) at altitude for sustained and transient exposure.

    - Fully explore the impact on OBOGS standard (max) 93% $O_2$ content on decompression sickness/pre-breathing requirements.

- Revalidate and make recommendations to clarify guidance for Air Standards with specific guidance on effect of systems deigned to minimum acceptable standards.
- Review and validate the implementation of performance based contract acquisition programs and risk analysis protocols.
- Examine those incidents that are occurring in flight regimes which are normally considered unlikely for a hypoxic event (e.g., 8,000 ft cabin altitude pressures).
- Review and validate all associated aircrew flight equipment affiliated with OBOGS-equipped aircraft.
- Priority should be given to the F-22 aircraft but expanding the scope to include the F-16, A-10, F-15E, B-1, B-2, CV-22, T-6, F-35, F-18 and other aircraft is authorized if appropriate.

## Study Products

Written, public-releasable report presented to the SAF/OS upon completion. A preliminary report provided to the SAF/OS by June 30, 2011 with follow-on reports provided every 60 days until completion. Planned completion in November 2011.

# Appendix J: Study Members

**Study Leadership**

Study Chair: General Gregory S. Martin, USAF (Ret)
Study Vice Chair: Lieutenant General George K. Muellner, USAF (Ret)

**Members and Consultants**

Major General Joseph T. Anderson, USMC (Ret)
Mr. James W. Brinkley
Honorable Dr. Lawrence J. Delaney
Dr. Peter F. Demitry, MD, MPH
Dr. David H. Moore
General Thomas S. Moorman, USAF (Ret)

**General Officer / Senior Executive Service Participants**

Major General Noel T. Jones, USAF, AF/A5R
Major General Robin Rand, USAF
Dr. Thomas P. Ehrhard, SES, AF/CC-SA

**Government Participant**

Colonel Eric A. Kivi, USAF, AFSC/SEF

**Study Support**

Lieutenant Colonel Edward J. Ryan, USAFR
Lieutenant Colonel Norman F. Shelton, USAF
Lieutenant Colonel Matthew E. Zuber, USAF
Major Christopher D. Forrest, USAF
Major Ryan W. Maresh, USAF
Major Brian T. Stahl, USAF
Captain Andrew Anderson, USAF
Mr. William M. Quinn

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# Appendix K: Study Meetings and Briefings

**<u>Overviews/Perspectives</u>**

<u>Air Force Leadership:</u>
Honorable Michael Donnelly
General Norman Schwartz, USAF

<u>Former/Current F-22 Chief Engineers:</u>
Mr. Eric Abell
Mr. Mark Fraker
Mr. Tim Keen
Mr. Bruce Peet
Mr. Jon Ogg

<u>Former/Current F-22 Program Managers</u>
Air Force Scientific Advisory Board
Lt Gen James A. Fain, USAF (Ret)
Lt Gen Thomas J. Owen, USAF
Lt Gen Robert F. Raggio, USAF (Ret)
Lt Gen C. D. Moore II, USAF
Brig Gen William J. Jabour, USAF (Ret)
Col Sean M. Frisbee, USAF

<u>Commander, Aeronautical Systems Center</u>
Lt Gen Tomas J. Owen, USAF

<u>Commander, Naval Air Systems Command</u>
Vice Admiral David Architzel, USN

**<u>HQ Air Force</u>**

SAF/AQR/AQX
AF/A3/5
AF/A4/7
AF/A9
AF/JA
AF/SG
AF/ST

**<u>USAF Major Commands</u>**

<u>Air Combat Command</u>
ACC/A3/A4/SG
9th AF/SE
1st FW/1st MXG/AFETS

<u>Air Education and Training Command</u>
AETC/A3/SG
59th MDTS
43rd FS

<u>Air Force Materiel Command</u>
AFMC/SG/SE
AFFTC/412th TW/F-22 CTF/95th AMDS
46th Test Wing
711th Human Performance Wing
ASC/F-22 SPO/EN/WI/WW/WN
AF Research Laboratory
USAF School of Aerospace Medicine

**<u>Other Air Force</u>**

AF Human Systems Integration Office
AF Institute of Technology
AF Safety Center
3rd FW/3rd AOG/3rd AMXS
302nd FS (USAFR)

**<u>Other DoD</u>**

F-35 Joint Program Office
OUSD (AT&L) / F-35
Naval Air Warfare Center
Naval Air Systems Command

**<u>Industry</u>**

Boeing
Cobham Mission Systems
Columbia Analytical Services
Honeywell
Lockheed Martin
Mayo Clinic
Pratt & Whitney
Wyle Corporation

**<u>Other Government/FFRDCs/Universities</u>**

Edgewood Chemical Biological Center
Lawrence Livermore National Laboratories
NASA Dryden Flight Research Center
NASA Houston Johnson Space Center
Sandia National Laboratories
University of Colorado
University of Tennessee

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# Appendix L: Glossary

The terms and associated definitions used herein were derived from various sources and reflect the collective judgment of the Air Force Scientific Advisory Board Aircraft Oxygen Generation Study Panel as what would appropriately reflect the intended meaning of the term within the context of this Study Final Report.

**13X Zeolite –** A type of synthetic zeolite used in On-Board Oxygen Generation Systems (OBOGS) systems. 13X Zeolite was first synthesized in 1950 and is readily available for use in commercial molecular sieves. See entries for Molecular Sieve and Zeolite.

**A-10 Thunderbolt II –** A United States Air Force (USAF) twin jet attack aircraft developed by Fairchild-Republic Company in the 1970s. Its primary mission is to provide close air support. The A-10 has a large amount of armor to protect the pilot and vital aircraft systems and was designed around a large 30 millimeter automatic cannon which forms the primary armament of the aircraft. A-10s have been upgraded with new avionics and many are also receiving a new wing. The USAF currently flies over 300 A-10 aircraft. The latest version, the A-10C, is being upgraded with an OBOGS to replace the previous liquid oxygen (LOX)-based system.

**Acquisition Lightning Bolts –** A series of nine acquisition improvement initiatives started in 1995 by the Assistant Secretary of the Air Force (Acquisition) to support the DoD's acquisition reform efforts. They were intended to streamline and improve acquisition and sustainment practices.

**Acquisition Improvement Plan –** An internal USAF effort to improve the capabilities and outcomes of its acquisition system. The plan has five main goals: (1) revitalize the acquisition workforce, (2) improve the requirements generation process, (3) instill budget and financial discipline, (4) improve Air Force major systems source selections, and (5) establish clear lines of authority and accountability within acquisition.

**Acute Exposure –** A single exposure to a substance (normally not lasting more than a day) that can result in severe biological harm or death (although the exposure may have no harmful result in a given instance). The Environment Protection Agency has established Acute Exposure Guideline Levels defining threshold exposure limits for the general public and that are applicable to emergency exposure periods ranging from 10 minutes to 8 hours.

**Advanced Medium-Range Air-to-Air Missile (AMRAAM) Vertical Eject Launcher (*A*VEL) *R*eplacement *I*nstrumentation *P*ackage (ARIP) –** ARIP is a pod carried on F-22 test aircraft that contains a variety of data recorders, processors, power supplies, transponder, and data telemetry equipment. The system forms the core of the F-22 test enterprise's capability to record and transmit flight test data.

**Advanced Tactical Fighter (ATF) –** The ATF program began in 1981 and was the precursor name for the acquisition program that eventually developed and produced the F-22 Raptor. It was a demonstration and validation program undertaken by the United States

Air Force to develop a next-generation air superiority fighter to counter emerging worldwide threats. Lockheed and Northrop were selected in 1986 to develop the YF-22 and the YF-23 demonstrator aircraft, respectively. These aircraft were evaluated in 1991 and the Lockheed YF-22 was selected and later developed into the F-22 Raptor.

**Air and Space Interoperability Council –** The Air and Space Interoperability Council (ASIC) is a formal five nation military organization with a mandate to enhance coalition warfighting capability through air and space interoperability. Member nations are those within the Five Eyes (United States, United Kingdom, Australia, New Zealand, and Canada) community and consist of representation from their respective Air Forces, and also includes the United States Navy. The ASIC was originally called the Air Standardization Coordination Committee. See entry for the Air Standardization Coordination Committee.

**Air Cycle Machine -** The refrigeration unit of the environmental control system used in pressurized gas turbine-powered aircraft. The air cycle cooling process uses air instead of a phase changing material such as Freon in the gas cycle meaning that no condensation or evaporation of a refrigerant is involved, and the cooled air output from the process is used directly for cabin ventilation or for cooling electronic equipment Normally hot compressed turbine engine bleed air is directed into a primary heat exchanger. Outside air at ambient temperature and pressure is used as the coolant in this air-to-air heat exchanger. Once the hot air has been cooled, it is then compressed. This compression heats the air and it is sent to the secondary heat exchanger, which again uses outside air as the coolant. See entry for Environmental Control System.

**Air Force Specialty Code –** An alphanumeric code used by the United States Air Force to identify an Air Force Specialty (AFS) applicable to officers or enlisted personnel. The AFSC is similar to the Military Occupational Specialty (MOS) used by the United States Army or Ratings used by the United States Navy. AFSC is sometimes used as shorthand for “required specific skill sets” or “job description” or “position description.”

**Air Standard –** A military aviation-related standard produced and distributed by the Air Standard Coordinating Committee now called the Air and Space Interoperability Council. See the entries for Air and Space Interoperability Council and Air Standard Coordinating Committee.

**Air Standard Coordinating Committee (ASCC) –** An organization formed in 1948 to manage the Air Standardization agreement between Canada, the United Kingdom, and the United States. The Agreement was intended to enable them to conduct combined air operations and provide each other with certain essential services. Also the ASCC promoted the economies that would result from standardizing air materiel support and encouraged the exchange of research and development information. The ASCC was expanded to include Australia in 1964 and New Zealand in 1965. See entry for Air and Space Interoperability Council.

**Aldehydes –** A class of organic compounds that contain the carbonyl group, and in which the carbonyl group is bonded to at least one hydrogen. Aldehydes are formed by partial oxidation of primary alcohols and form carboxylic acids when they are further oxidized. Aldehydes are used for the manufacture of synthetic resins (e.g., Bakelite), and for

making dyestuffs, flavorings, perfumes, and other chemicals. Some are used as preservatives and disinfectants.

**Alkanes –** A class of organic substances (also known as paraffins or saturated hydrocarbons) are chemical compounds that consist only of hydrogen and carbon atoms and are bonded exclusively by single bonds (i.e., they are saturated compounds). The simplest alkane is methane. Saturated oils and waxes are examples of larger alkanes. Alkanes are not very reactive and have little biological activity.

**Alkenes –** An unsaturated chemical compound containing at least one carbon-to-carbon double bond. The simplest alkene is ethylene.

**Alkynes** – Hydrocarbons that have a triple bond between two carbon atoms. One example of an alkyne is acetylene.

**Alveolar Gas Equation –** The partial pressure of oxygen in the pulmonary alveoli ($P_AO_2$) of the human lung is required to calculate both the alveolar-arterial gradient of oxygen and the amount of right-to-left cardiac shunt, which are both important in determining susceptibility to and evidence of hypoxia. However it is not practical to take a sample of gas from the alveoli in order to directly measure the partial pressure of oxygen. The alveolar gas equation was first characterized in 1946 and allows the calculation of the alveolar partial pressure of oxygen from data that is practically measurable. The alveolar gas equation is:

$$P_AO_2 = ( F_iO_2 * (P_{atmos} - P_{H2O})) - (P_aCO_2 / RQ)$$

where $F_iO_2$ is the fraction of inspired oxygen, $P_{atmos}$ is the ambient atmospheric pressure, and $P_{H2O}$ is the water vapor pressure at 37°C. The respiratory quotient (RQ) is the ratio of $CO_2$ eliminated divided by the $O_2$ consumed.

**Argon –** A chemical element that is found in gaseous form within the Earth's atmosphere and is the third most common gas in the atmosphere (about 1 percent). Argon is considered an inert gas at normal atmospheric pressure, as it is stable and resistant to bonding with other elements. OBOGS systems concentrate Argon as a byproduct of their oxygen concentration processes. In the F-22 the OBOGS product air can be almost 6 percent Argon by volume when the system is producing its maximum concentration of Oxygen.

**Automatic Ground Collision Avoidance System (AGCAS) –** AGCAS is a software application that keeps track of the aircraft's position, speed, and altitude against a digital terrain map of the Earth. The system intervenes if the pilot becomes disoriented, or suffers a G-induced loss of consciousness. A pilot warning is issued a specified period of time (a few seconds) before the flight computer takes control of the aircraft. If the pilot fails to react to the warning the auto-GCAS system takes control of the aircraft. In general the AGCAS will immediately roll the aircraft to a wings-level orientation and initiates a vigorous pull-up maneuver. The computer gives control back to the pilot after it restores the aircraft's stability. An AGCAS is set to be implemented on certain F-16 blocks, the F-22, and the F-35.

**Auxiliary Power Unit (APU) –** A device on an aircraft that provides electrical power or compressed air (or both) for functions other than propulsion. They are commonly found on larger aircraft, but can also be installed on fighter-type aircraft as well. APUs usually help free an aircraft from reliance on ground power units for engine start and other

purposes and can provide "housekeeping power" for the environmental control system, electrical, and hydraulic systems when the main propulsion system(s) are not operating.

**AV-8B –** The Boeing AV-8B Harrier II is a single-seat, single engine second-generation vertical/short takeoff and landing ground-attack aircraft flown by the United States Marine Corps. It utilizes an OBOGS system to provide breathing oxygen to the pilot.

**Aviation Breathing Air Standard –** A not-yet produced but recommended Air Standard to be developed by the United States Air Force Research Laboratory and put forward to the five-nation Air Standard Coordinating Committee (ASCC) See entry for the ASCC.

**Aviation Physiology –** Aviation physiology is the medical/scientific discipline that deals with the physiological challenges encountered by pilots and passengers when subjected to the environment and stresses of flight, especially high-human stress aviation activities such as military tactical flight operations (high altitude, rapid pressure changes, high g-loading, etc.).

**B-1B –** The Boeing B-1B Lancer is a variable-sweep wing bomber used by the United States Air Force (USAF). It has four turbofan engines and employs a blended wing-body design to achieve a maximum speed of about Mach 1.25 and is optimized for low level penetration. The B-1B has a normal aircrew of four and is currently used only in a non-nuclear role. The B-1B generates its own breathing oxygen for crew use via an OBOGS-type system.

**B-2A Spirit –** The B-2A is a multi-role bomber flown by the USAF. It is capable of delivering both conventional and nuclear munitions. Its low-observable, or "stealth," characteristics give it the ability to penetrate sophisticated defenses and threaten heavily defended targets. The B-2's low observability is derived from a combination of reduced infrared, acoustic, electromagnetic, visual, and radar signatures. The B-2 utilized and OBOGS system to provide breathing oxygen to the aircrew.

**Backup Oxygen System (BOS) –** A BOS provides oxygen to the aircrew (and if applicable, passengers) in the absence or failure of the primary life support system(s) that normally provides breathing air. A BOS may use gaseous or liquid oxygen, depending on design, and its operating duration is generally in the 10-60 minute range. The BOS can be recharged on the ground via a maintenance action or (in some systems) in the air by the primary system once full operational function is restored (in-air restoration applies mainly to OBOGS type primary systems). In a fighter-type aircraft a BOS may be aircraft or ejection seat-mounted.

**Bleed Air –** Compressed air extracted from the compressor section (i.e., prior to fuel injection and combustion) of a gas turbine engine. Bleed air is usually at a relatively high pressure and temperature and can be used for deicing, cabin pressurization, etc. For many uses (cabin air, environmental control system, avionics cooling, etc.) the bleed air must first be cooled by the environmental control system. See the entry for Environmental Control System.

**Bottom Up Review –** In 1993 Secretary of Defense initiated a comprehensive review of the nation's defense strategy, force structure, modernization, infrastructure, and foundations. The results of this "Bottom Up Review" provided a basis for a reassessment of defense concepts, plans, and programs and was used as the basis/rationale for a large number of significant DoD program, budget, and resource changes and reductions.

**Breathing Regulator Anti-G (BRAG) Valve –** In the F-22, the pilot is equipped with an integrated, fast acting BRAG valve that controls the flow of air to the mask, the counter-pressure vest, and the G-suit, the latter acting as a partial pressure suit at high altitude.

**Broad Area Review (BAR) –** A group of highly qualified individuals with a broad background of experience in the issues/programs to be reviewed and analyzed. Normally the members are all government (military and civilian) personnel although sometimes outside industry or other experts are asked to serve as advisors. This is in contrast to a review by a group chartered under the Federal Advisory Committee Act (such as the Defense Science Board or the AF Scientific Advisory Board) where none of the members may be government employees (although a few government personnel are sometimes asked to serve as advisors). Also a BAR and its members, given that they are government employees, are not necessarily considered to be offering independent advice to their government sponsor (which does not inhibit most BARs, in practice, from being quite objective).

**Built In Test (BIT) –** A mechanism that permits a machine (mechanical or electronic) to test itself. BIT is commonplace in weapons, avionics, medical devices, automotive electronics, complex machinery of all types, unattended machinery of all types, and integrated circuits.

**C2A1 Filter –** A system designed to filter breathing air, originally certified for use in a chemically contaminated warfare environment. The filter has been tested against military and National Institute for Occupational Safety and Health protocols, and found to be effective against a number of different chemical warfare and industrial chemicals. It was temporarily incorporated into the F-22 pilot life support system to filter potential contaminants, with the filter (a high efficiency particulate filter material combined with activated carbon and charcoal for chemical absorption) being replaced after each flight. The filter is no longer being used routinely in the F-22.

**Cabin/Cockpit Pressure –** A measure (usually expressed in feet of altitude, e.g., "a cabin altitude of 5,000 feet") of the atmospheric pressure being maintained in the aircrew compartment by an aircraft's environmental control system. Most current commercial aircraft can maintain an internal (cabin) altitude/pressurization of about 8,000 feet up to an actual aircraft altitude of 40,000 feet. In general, if the cabin altitude cannot be maintained below a set level (often 10,000 feet) supplemental oxygen is usually required. Tactical aircraft usually operate at a higher cockpit altitude to reduce the deleterious airframe and aircrew effects of a rapid or explosive decompression due to battle damage. The F-22 operates with a cabin altitude between sea level and no higher than 25,000 feet depending on the actual altitude at which it is flying. Normally the life support system provides the pilot, through his oxygen mask, whatever supplemental oxygen is required.

**Carbon Dioxide ($CO_2$) –** A naturally occurring chemical compound composed of two oxygen atoms covalently bonded to a single carbon atom. $CO_2$ is a gas at standard temperature and pressure and exists in Earth's atmosphere in this state, as a trace gas at a concentration of 0.039% by volume. Plants absorb carbon dioxide and produce oxygen. Carbon dioxide is also produced by combustion of coal or hydrocarbons (such as occurs in jet engines). $CO_2$ is an asphyxiant gas and not classified as toxic or harmful in low

concentrations. Concentrations of 7% to 10% may cause suffocation, manifesting as dizziness, headache, visual and hearing dysfunction, and unconsciousness within a few minutes to an hour.

**Carbon Monoxide, Carbon Monoxide Poisoning –** Carbon monoxide (CO) is a product of incomplete combustion of organic matter due to insufficient oxygen supply to enable the complete oxidation of $CO_2$. CO is a colorless, odorless, and tasteless gas and therefore difficult for a human to detect. Carbon monoxide mainly causes adverse effects by combining with hemoglobin to form carboxyhemoglobin in the blood. This prevents oxygen binding to hemoglobin, reducing the oxygen-carrying capacity of the blood, leading to hypoxia. Symptoms of mild acute poisoning can include lightheadedness, confusion, headaches, vertigo, and flu-like symptoms. Higher exposures can lead to significant toxicity and even death.

**Carboxyhemoglobin Level –** Carboxyhemoglobin is hemoglobin combined with carbon monoxide. The carboxyhemoglobin level is a measure of the amount of carbon monoxide which has been absorbed into the blood stream. Because carbon monoxide has a much greater affinity to bind to hemoglobin than oxygen, even small amounts of carbon monoxide will significantly reduce the blood's ability to transport needed oxygen within the body.

**Central Nervous System (CNS) –** The CNS consists of the brain and the spinal cord and contains the majority of the neurons in the body.

**Combat Edge –** A set of specially designed pilot-worn life support equipment designed to improve tolerance to high-G maneuvers and help prevent G-induced loss of consciousness. The system is intended to provide pilots greater endurance during high-performance maneuvers up to +9 Gs.

**Combined Test Force –** A test organization in which all test stakeholders (contractor, government operational and development testers, and government users) are represented. Test assets and test infrastructure are shared. This reduces the infrastructure and test asset needs compared to the situation that would exist if each stakeholder had to purchase and operate its own infrastructure and test assets. Test planning is done cooperatively and test missions may collect data for multiple stakeholders on the same mission. Although planning and conduct of test missions are cooperative, and data is shared; data analysis, evaluation, and test reporting are usually independent activities conducted by each stakeholder to support their own objectives and interests.

**Commercial Off the Shelf (COTS) –** Software or hardware, technology, or other products that are ready-made and available for sale, lease, or license to the general public. COTS items require no unique government modifications or maintenance over the life cycle of the product to meet the needs of the procuring agency. Motivations for using COTS components include reduction of overall system development and costs. There are sometimes maintenance cost advantages to using COTS equipment, but since the lifecycle of COTS systems are determined by public desire, they can be subject to availability issues after some period of time.

**CPK Equation –** The Coburn-Forster-Kane (CPK) equation is the most sophisticated approach currently available to model carbon monoxide uptake by humans and animals.

**CRU-93 –** A diluter-demand, g-compensated oxygen regulator that provides automatic pressure breathing as a function of both altitude and G-forces. The pressure breathing for G function is activated by a pressure signal from an external anti-G valve and is used with an USAF counter-pressure vest and high pressure mask/helmet assembly to form the "COMBAT EDGE" ensemble. This regulator is currently being used on the F-16A/B/C/D.

**CRU-94 –** An integral component of the Combat Edge System is the CRU-94/P. Providing pressure breathing for G capability to tactical aircrew, it reduces the probability of G-induced loss of consciousness during high performance flight. It is specifically designed to distribute pressurized breathing gas from the aircraft-mounted regulator to the pilot's oxygen mask and bladders, located in the vest and lightweight HGU-55/P helmet, which is specially configured for Combat Edge.

**CRU-98 –** In addition to pressure breathing as a function of altitude and air dilution features, this regulator incorporates pressure breathing as a function of G (PBG). With this added feature the regulator receives a pressure input signal from a remotely located G-valve to provide the appropriate PBG outlet pressure. This regulator is used on the F-15 MSOGS and F-16 OBOGS aircraft.

**CRU-120 –** This personal connector combines the features of the CRU-94/P Integrated Terminal Block with the CRU-79 Oxygen Regulator. It allows the Combat Edge ensemble to interface with a regulated emergency oxygen system. Operation of the CRU-79 oxygen regulator significantly improves pilot breathing comfort during emergency conditions while extending the emergency oxygen duration. It is currently installed on the US Air Force F-16.

**CRU-122 –** The CRU-122 allows the Combat Edge ensemble to interface with a regulated emergency system and provides an important role in oxygen backup. It supplies oxygen at a slight positive pressure, preventing inward leakage and improving pilot breathing comfort during emergency conditions. This personal connector extends the emergency oxygen duration while automatically increasing positive pressure above 40,000 feet. The CRU-122 is currently installed on the F-22.

**Defense Acquisition Board –** The DAB is the DoD's senior-level forum for advising the Under Secretary of Defense for Acquisition, Technology, and Logistics on critical decisions concerning major defense acquisition programs. The DAB is composed of the DoD's senior executives including the Service Secretaries and the Vice Chief of the Joint Chiefs of Staff.

**Data Transfer Cartridge (DTC) –** The F-22's DTC is located in the cockpit and used to upload and download operational, maintenance, and other data. With regard to maintenance of the F-22, during a mission various faults in the aircraft systems are noted and recorded by its on-board maintenance systems for later analysis and diagnostic activities. This fault data is transferred to and archived in the DTC during the mission. When a pilot returns from a mission, the DTC is removed and brought to the maintenance activity. If any failures occurred on the mission, those fault codes have been noted in the DTC and that data is downloaded into the maintenance support cluster computer so the cause of the failure can be identified.

**Demonstration/Validation (DemVal) –** A term used in a previous version of the Defense Acquisition System (circa 1990) that was the second phase in the acquisition life cycle. It consisted of the steps necessary to resolve or minimize logistics problems identified during Concept Exploration and Definition, verify preliminary Design and Engineering, build prototypes, accomplish necessary planning, and fully analyze trade off proposals. The objective of DEMVAL was to validate the choice of alternatives and to provide the basis for determining when to proceed into Engineering and Manufacturing Development.

**Desorption Tube –** A means for trapping (absorbing) potential volatile organic compounds over a given sampling period. Once the samples are collected the tubes are capped and taken to an analysis facility and heated. The non-reactive, inert absorbent matrix inside the tube then "desorbs" the compounds (if any) allowing them to be measured and analyzed. Desorption tubes were used extensively in F-22 OBOGS testing at Edwards AFB and other locations.

**Dienes –** In organic chemistry a diene is a hydrocarbon that contains two carbon double bonds. Dienes occur occasionally in nature but are widely used in the polymer industry.

**DoD Acquisition Milestones (A, B, and C // I, II, and III) –** The management framework for defense systems acquisition is commonly referred to as the acquisition life cycle. The acquisition life cycle of the F-22 was sufficiently lengthy that is was developed under two different DoD acquisition milestone systems. The current DoD life cycle process consists of phases separated by decision points called milestones. Milestones (MS) established by Department of Defense Instruction 5000.02 are:

- **MS A** approves entry into the Technology Development phase,
- **MS B** approves entry into the Engineering and Manufacturing Development phase (Note: formal program initiation normally occurs at MS B), and
- **MS C** (formerly MS III) approves entry into the Production and Deployment phase.

The above contrasts with the previous DoD acquisition system:

- **Milestone 0** approves entry into the Concept Exploration phase,
- **Milestone I** approves entry into the Program Definition and Risk Reduction phase,
- **Milestone II** approves entry into the Engineering and Manufacturing Development phase, and
- **Milestone III** approves entry into the Production, Fielding, and Support phase.

**Emergency Oxygen System (EOS) –** An EOS provides oxygen to the aircrew (and if applicable, passengers) in the absence or failure of the primary life support system that normally provides breathing air and after failure of the back-up oxygen system if so equipped. An EOS normally is designed to use gaseous oxygen and its operating duration is generally in the 10-15 minute range. The EOS can be recharged on the ground via a maintenance action. In a fighter-type aircraft an EOS is generally ejection seat-mounted as it also provides breathing air to the pilot during and after ejection. See Backup Oxygen System entry.

**Engineering and Manufacturing Development (EMD) Phase –** In DoD acquisition, EMD begins at Milestone B, which is normally formal program initiation. This phase is intended to complete the development of a system or increment of capability complete full system integration, develop an affordable and executable set of manufacturing processes, complete system fabrication, and start test and evaluation. In EMD, the program, the system architecture, and system elements down to the configuration item (hardware and software) level are defined, system design requirements are allocated down to the major subsystem level and are refined as a result of developmental and operational tests and iterative systems engineering analyses. The support concept and strategy are refined with detailed design-to requirements determined for the product support package elements.

**Environmental Control System –** The Environmental Control System (ECS) of an aircraft provides air supply, thermal control, and cabin pressurization for the crew and passengers. Avionics cooling, smoke detection, and fire suppression are often considered part of an aircraft's ECS. On most turbine-powered aircraft, air is supplied to the ECS by being "bled" from a compressor stage of the gas turbine engine, upstream of the combustor. The temperature and pressure of this "bleed air" varies widely depending upon which compressor stage is being utilized and the power setting of the engine.

Specific to the F-22 ECS:

The F-22 uses an integrated ECS that provides thermal conditioning throughout the flight envelope for the pilot and the avionics. The ECS accomplishes avionics cooling, provision of air to the pilot; canopy defogging, cockpit pressurization; and fire protection.

The air cycle system takes engine bleed air (which is between 1,200-to-2,000 degrees Fahrenheit) and cools it to approximately 400 degrees via a heat exchanger. From there the air goes into an air cycle refrigeration machine (which also removes any water) and comes out at about 50 degrees. This cooled air is also fed into the OBOGS to provide breathable oxygen to the pilot, to operate the Breathing Regulator/Anti-G valve, to provide canopy defogging, and to provide cockpit pressurization.

A liquid cooling system is also a part of the overall F-22 ECS. Polyalphaolefin (PAO) is the medium used in the liquid cooling system. One loop cools the mission critical avionics and keeps them at about 68 degrees F. The PAO passes through a vapor cooling system and a filter and is routed to the F-22 avionics and then out to the wings to cool the embedded sensors before entering the second cooling loop. The PAO then is routed to the fuel tanks, where the heat is transferred to the fuel (used as a heat sink).

The now-warm fuel is circulated through an air-cooled heat exchanger (which utilizes cool/cold air taken from the boundary layer diverter between the inlet and the F-22's forward fuselage) to cool the fuel. Another loop is used to cool the engine lubricants.

**Epidemiological –** Relating to epidemiology, the branch of medicine that deals with the study of the causes, distribution, and control of disease or other medical conditions in human populations.

**Esters –** A common type of chemical compound formed by condensing an acid with an alcohol. Esters are widespread in nature and are widely used in industry and are encountered daily by most people. For example, most naturally occurring fats and oils are the fatty acid

esters of glycerol. Esters with low molecular weight are commonly used as fragrances and found in essential oils. Phosphoesters form the backbone of DNA molecules. Nitrate esters, such as nitroglycerin, are known for their explosive properties, while polyesters are important plastics.

**F-15C/D/E –** The F-15 Eagle is an all-weather tactical fighter designed to gain and maintain air superiority in aerial combat. The F-15C Eagle is an updated version of the F-15A. It entered the Air Force inventory beginning in 1979 and has many improvements including additional internal fuel, provision for carrying exterior conformal fuel tanks and increased maximum takeoff weight. Additional enhancements include an upgraded central computer; ability to employ advanced versions of various air-to-air missiles; an expanded electronic warfare system, and radar improvements. The F-15E is a two-crew version optimized for air-to-ground attack. The F-15E utilizes an OBOGS-type system.

**F-16C/D (Block 40, Block 50) –** The F-16 Fighting Falcon is a multi-role tactical fighter aircraft flown by the USAF and numerous other Air Forces around the world. The F-16 Block 40 series is the improved all-day/all-weather strike variant equipped with LANTIRN pod and features strengthened and lengthened undercarriage, an improved radar, and a Global Positioning System (GPS) receiver. Block 50 F-16s are have an improved GPS/Inertial Navigation System, and the ability to carry additional advanced munitions such as the AGM-88 High speed Anti-Radiation Missile, Joint Direct Attack Munition, Joint Stand Off Weapon, and Wind Corrected Munitions Dispenser. Some versions of the F-16 employ an OBOGS type system.

**F-18C/D/E/F/G –** The Boeing F/A-18 Hornet is a twin-engine carrier-capable multirole fighter jet, designed for fleet air defense, air superiority, and ground attack missions. The F/A-18C/D Hornet provided the baseline design for the F/A-18E/F Super Hornet, a larger, evolutionary redesign of the F/A-18. Compared to the Hornet, the Super Hornet is larger, heavier and has improved range and payload. The Boeing EA-18G Growler electronic jamming platform was also developed from the F/A-18E/F Super Hornet. The F-18E/F/G uses an OBOGS system to provide the crew with breathing oxygen.

**F-22 –** The F-22A Raptor is a USAF fighter aircraft that uses stealth technology. It is primarily an air superiority fighter but has multiple capabilities including ground attack. It normally carries its munitions internally to preserve its stealth characteristics but can carry additional munitions on external hard points if required. The F-22 employs an OBOGS to provide oxygen to the pilot.

**F-35 –** The F-35 Lightning II is a single-seat, single-engine, stealth capable military strike fighter aircraft currently in development for the USAF and other Services as well as several foreign countries. It is a multi-role aircraft that can accomplish close air support, tactical bombing, and air superiority. The F-35 employs an OBOGS to provide oxygen to the pilot.

**Failure Mode Effects and Criticality Analysis (FMECA) –** FMECA was originally developed in the 1940s by the US military. It is an extension of failure mode and effects analysis (FMEA). FMEA is a bottom-up, inductive analytical method which may be performed at either the functional or piece-part level. FMECA extends FMEA by including a criticality analysis, which is used to chart the probability of failure modes against the severity of their consequences. The result highlights failure modes with relatively high

probability and severity of consequences, allowing remedial effort to be directed where it will produce the greatest value.

**Federal Acquisition Regulations –** The principal set of rules in the Federal Acquisition Regulation System. This system consists of sets of regulations issued by agencies of the federal government of the United States to govern the acquisition process for goods and services. The FAR System regulates the activities of government personnel in carrying out that process. It does not regulate the purchasing activities of private sector firms, except to the extent that portions of the FAR are incorporated into government solicitations and contracts by reference. The FAR is codified in Title 48 of the United States Code of Federal Regulations; and the FAR and its agency supplements are said by the federal courts to have "the force and effect of law." Nearly all government agencies are required to comply with the FAR in the acquisition of services and goods.

**Fiscal Year (FY) –** For the United States Government, the period covering 1 October to 30 September (12 months).

**Fly-To-Warn / Fly-To-Fail –** A design technique whereby a mission system, subsystem, or part will be considered to be operational until an external indication of an impending or actual partial or total performance malfunction is received. If a system is designed to be or shown to be inherently very reliable and maintenance free this technique can greatly reduce costs by the elimination of having to replace parts/systems on a schedule-based or use-based basis. Many modern complex systems employ this design philosophy. For example, commercial aircraft engines used to be removed, overhauled, and replaced strictly on an operating hour basis. Now they usually remain "on-wing" until a warning of an impending failure is received or an actual failure is experienced. Normally, employment of this technique requires that the system be very well understood and all its operating and failure modes be well characterized.

**Follow-On Operational Test and Evaluation –** The Test and Evaluation efforts that may be necessary after the Full-Rate Production Decision Review to refine the estimates made during Operational Test and Evaluation, to evaluate changes, and to reevaluate the system to ensure that it continues to meet operational needs and retains its effectiveness in a new environment or against a new threat.

**Form 107, 107 Team –** The Form 107, Request for Engineering Technical Assistance is used for two types of assistance needs: for Technical Assistance (TAR) and for Maintenance Assistance (MAR). A TAR is used for engineering support/disposition and a MAR requests depot maintenance action. The Form 107 provides advice, assistance, disposition, and training pertaining to installation, operation, and maintenance of equipment using authorized procedures. It can also provide authorization for one-time repairs or time definite repair opportunities beyond what is spelled out in existing technical orders and can also provide the one-time authority to use a specific part/commodity with defects or deviations beyond technical order limits and/or provide authorization for limited use of non-listed substitutes (supplies, components, support equipment, etc.) to prevent mission impairment. A multi-disciplinary "107 Team" may put together and can perform as a relatively long-term technical and maintenance task team depending on the severity and urgency of the problem to be addressed.

**Full Operational Capability (FOC) –** FOC is achieved when all intended users (by agreement between the developer and the user) have the intended operational capability. See entry for Initial Operational Capability.

**Functional Management Inspection (FMI) –** An evaluation of a particular function/practice/program and how effectively it is being performed, sometime restricted to a particular sub-organization or location, or sometimes evaluating the totality of that function throughout a large organization. An FMI is normally conducted by an outside evaluation organization such as the Office of the Inspector General. Examples have included FMIs for all USAF Base Facility Energy programs, all Base Child Care Facilities throughout the Air Force, Intelligence Support to Systems Acquisition, etc.

**G-Suit –** A flight suit worn by aircrew subject to high levels of acceleration force due to aircraft maneuvering. It is designed to prevent a loss of consciousness caused by the blood pooling in the lower part of the body when under acceleration, thus depriving the brain of blood which in turns leads to temporary hypoxia. A G-suit generally takes the form of tightly-fitting trousers fitted with inflatable bladders which, when pressurized through a G-sensitive valve, constrict on the abdomen and legs, thus restricting the draining of blood away from the brain during periods of high acceleration. In addition, in some modern fighters capable of very high sustained G maneuvers, the G-suit effect is augmented by a small amount of pressure applied to the lungs (partial pressure breathing), which also enhances resistance to high G.

**Goldwater-Nichols –** "Shorthand" for the Goldwater-Nichols Department of Defense Reorganization Act of 1986, which reorganized the command structure of the DoD. It increased the powers of the Chairman of the Joint Chiefs of Staff and implemented some of the suggestions from The Packard Commission. Operational authority was centralized through the Chairman of the Joint Chiefs as opposed to the Military Service Chiefs. The Chairman was designated as the principal military advisor to the President, National Security Council, and Secretary of Defense. The Act established the position of Vice-Chairman and streamlined the operational chain of command from the President to the Secretary of Defense to the Unified Command Commanders (now Combatant Command Commanders). It also established certain Service headquarters functions as being under the sole purview of the Secretaries of the Military Services (removing the Military Chiefs of the Services from any formal role in these areas), including Acquisition, Comptroller, Information Management, Auditing, Public Affairs, and Legislative Affairs. See the entry for Packard Commission.

**Graywolf TG-501 –** A multi-gas capable sensing monitor from GrayWolf Sensing Solutions, LLC. It is capable of measuring the presence/concentration of a wide variety of potentially toxic gases including Ozone, Ammonia, Sulfur Dioxide, Carbon Monoxide, Hydrogen Sulfide, Hydrogen Cyanide, Carbon Dioxide, Oxygen, etc.

**Halogenated Anesthetics –** At room temperatures, halogenated anesthetics are typically clear, colorless, mainly non-odorous, and highly volatile liquids. Examples include isoflurane, halothane, enflurane, desflurane, and sevoflurane.

**Hardware-In-The-Loop –** Hardware-In-the-Loop (HIL) is a form of real-time simulation. HIL differs from pure real-time simulation by the addition of a real component in the loop. The purpose of a Hardware-In-the-Loop system is to provide all of the electrical and

other stimuli needed to fully exercise a component (mechanical, electrical, hydraulic, or electromechanical). The effect (for the unit being evaluated) is that it "thinks" that it is in its actual intended environment (pressure, temperature, etc.) and all/most external input is provided via real hardware.

**Human Factors –** The comprehensive integration of human capabilities and limitations (cognitive, physical, sensory, and team dynamic) into system design, development, modification, and evaluation to optimize human-machine performance for both operation and maintenance of a system. Human Factors Engineering designs systems that require minimal manpower, provide effective training, can be operated and maintained by users, and are suitable and survivable.

**Human System Integration (HSI) –** A process to ensure systems are designed and developed that effectively and affordably integrate with human capabilities and limitations. The HSI process considers human factors engineering, manpower, personnel, training issues, and environment, safety and occupational health aspects.

**Hyperventilatory Response –** Hyperventilation (or "overbreathing") in humans can be in response to stress or other conditions. Hyperventilation can cause symptoms such as numbness or tingling in the hands, feet and lips, lightheadedness, dizziness, headache, chest pain, spasm of hands and feet, slurred speech, and sometimes fainting. These effects are not caused by lack of oxygen or air. Rather, faster or deeper breathing than normal can cause excessive expulsion of circulating carbon dioxide. Lowering carbon dioxide reduces the acidity of the circulating blood. Low acidity (the proxy for low carbon dioxide levels) causes the brain's blood vessels to constrict, resulting in reduced blood flow to the brain and lightheadedness. The low acidity value resulting from hyperventilation also reduces the level of available calcium, which affects the nerves and muscles, causing constriction of blood vessels and tingling.

**Hypoxia –** Hypoxia is a condition in which the body is deprived of adequate oxygen supply. The symptoms of generalized hypoxia depend on its severity and acceleration of onset. In the case of altitude sickness, where hypoxia develops gradually, the symptoms include headaches, fatigue, shortness of breath, a feeling of euphoria and nausea. Generalized hypoxia occurs in healthy people when they ascend to high altitude or when breathing mixtures of gases with a low oxygen concentration. Hypoxia can also occur when there is adequate oxygen, but poor tissue perfusion or when there is exposure to toxic levels of certain chemicals (e.g., Carbon Monoxide or Cyanide).

**Inherently Governmental Responsibility –** In general, such inherently government functions would include those that substantially or wholly involve activities that:

- Involve exercising the sovereign power of the federal government to include determining, protecting, or advancing United States interests by military, police, contract management action, or
- Significantly affect the life, liberty, or property of private persons, or
- Exert ultimate control over the disposition of federal property.

Examples of functions considered to be inherently governmental functions or which the federal government has directed as to be treated as such include:

- Direct conduct of criminal investigations.

- Control of prosecutions and performance of adjudicatory functions other than those relating to arbitration or other methods of alternative dispute resolution.
- Command of military forces, especially the leadership of military personnel who are members of the combat, combat support, or combat service support role.
- Conduct of foreign relations and the determination of foreign policy.
- Determination of Agency policy, such as determining the content and application of regulations, among other things.
- Determination of Federal program priorities for budget requests.
- Direction and control of Federal employees.
- Direction and control of intelligence and counter-intelligence operations.
- The determination of what Government property is to be disposed of and on what terms (although an agency may give contractors authority to dispose of property at prices within specified ranges and subject to other reasonable conditions deemed appropriate by the agency).
- Approval of Federal licensing actions and inspections.
- Determination of budget policy, guidance, and strategy.

**Initial Operational Capability –** The first attainment of the capability to employ effectively a weapon, item of equipment, or system of approved specific characteristics that is manned or operated by an adequately trained, equipped, and supported military unit or force.

**Initial Operational Test and Evaluation (IOT&E) –** Dedicated operational test and evaluation conducted on production or production representative articles, using typical operational scenarios, to determine whether systems are operationally effective and suitable. It immediately precedes the full-rate production decision. IOT&E is conducted by an OT&E agency independent of the contractor, program management office, or developing agency.

**Integrated Caution, Advisory, and Warning (ICAW) –** The F-22 ICAW system filters unnecessary detail and duplication to inform the pilot of a fault. This reduces pilot workload by presenting only what information regarding system and subsystem operation and status that the pilot needs to know. Up to 12 ICAW messages can be displayed at the same time. An ICAW warning to the pilot may be evidenced by an aural or visual indication or both.

**Integrated Product Team (IPT) –** A multidisciplinary group of people who are collectively responsible for delivering a defined product or process. IPTs are used in complex development programs/projects for review and decision making. The emphasis of the IPT is on involvement of all stakeholders (users, customers, management, developers, etc.) in a collaborative forum. An IPT is empowered to make critical life cycle decisions for the development of a product or system.

**Ketones –** An organic compound with the general formula of CnH2nO. Ketones are of great importance in industry and in biology. Examples include many sugars (e.g., fructose) and the industrial solvent acetone. Ketones are pervasive in nature and are necessary for photosynthesis to occur in plants. Ketones are produced on massive scales in industry as solvents, polymer precursors, and pharmaceuticals. In general, any hydrocarbon combustion process gives off a variety of ketones. Simple ketones, with a few

exceptions, are not highly toxic, which is a reason for their relatively wide-spread use as solvents.

**Key Performance Parameter (KPP) –** Those attributes or characteristics of a system that are considered critical or essential to the development of an effective military capability. A KPP normally has a threshold, representing the required value, and an objective, representing the desired value. KPPs are contained in the Capability Development Document and the Capability Production Document and are included verbatim in the Acquisition Program Baseline. Certain KPPs may be “mandatory” or “selectively applied,” depending on the system.

**Life Support System –** A fighter aircraft life support system (such as that installed in the F-22) is intended to sustain the activities of and protect the life/health of the aircrew by providing a pressurized environment, heated/cooled and filtered breathing air as required, supplemental oxygen as needed, anti-G protection, anti-flash protection, and other support needed to enable the continued performance and sustain the life of the aircrew.

**Life Sustainment System –** The life sustainment system includes the F-22 environmental control system plus the life support system.

**LOX System –** Liquid oxygen (LOX) systems were commonly used in military aircraft to provide breathing oxygen to the crew, starting in the 1950s. While effective in meeting their purpose, aircraft LOX systems were logistically expensive and sometimes complex to support (each base had to have a liquid oxygen generating plant) and the aircraft systems were sometimes dangerous to maintain/replenish. Also, mission accomplishment was dependent on the availability of a liquid oxygen plant. For each tactical base, the LOX plants represented a single point of vulnerability against which an enemy could target. For these and other reasons the US Air Force began moving towards “self-sufficiency” for new-design aircraft in the 1980s. Each aircraft would generate its own needed breathing oxygen, thus decreasing overall mission vulnerabilities and reducing logistics footprint and cost for expeditionary forces.

**Manpower, Personnel, and Training (MPT) Factors –** MPT factors are components of the discipline of human factors integration. They are usually considered early in the weapon system acquisition process, especially in the design of the system and specifically in the operator/sustainer-system interface.

**Mean Time Between Failures (MTBF) –** The predicted (or experienced) elapsed time between inherent failures of a system during operation. MTBF can be calculated as the arithmetic mean (average) time between failures of a system. The definition of MTBF depends on the definition of what is considered a system failure. For complex, repairable systems, failures are considered to be those out of design conditions which place the system out of service and into a state for repair. Failures which occur that can be left or maintained in an unrepaired condition, and do not place the system out of service, are not considered failures.

**Milestone A –** A DoD acquisition program milestone is a point at which a recommendation is made and approval sought regarding starting or continuing an acquisition program, i.e., proceeding to the next phase. Milestone A is that decision point that approves entry into the Technology Development phase.

**Military Specification (Mil-Spec) –** A document that describes the essential technical requirements for purchased materiel that is military unique or substantially modified commercial items.

**Military Standard (Mil-Std) –** A document that establishes uniform engineering and technical requirements for military-unique or substantially modified commercial processes, procedures, practices, and methods. There are five types of defense standards: interface standards, design criteria standards, manufacturing process standards, standard practices, and test method standards.

**Mission Design Series –** A series of numbers and letters that describe the basic mission of the aircraft, modifications to the aircraft, manufacturer, etc. These numbers and letters represent the Mission Design Series (MDS). All US military aircraft were given a two-part MDS symbol or designation when the Department of Defense unified all military aircraft designations under a common designation system. The first part is a letter which tells the kind of aircraft (mission) and the second part is a number which tells the model (model) of the aircraft. A third character (letter) designates the variant. For example, the MDS of F-15C indicates a fighter aircraft, 15$^{th}$ fighter design, and the third variant. Some MDS variants represent only a paper proposal and may not have actually been flown, manufactured, or even fully designed, leading to "jumps" in the sequence of actual fielded MDS nomenclatures.

**Molecular Sieve Oxygen Generating Systems (MSOGS) –** Molecular sieve oxygen generating systems are replacing liquid oxygen systems as the principal method for the production of breathable oxygen on-board military aircraft. These systems separate oxygen from aircraft engine bleed air by application of pressure swing adsorption technology. Oxygen is concentrated by preferential adsorption of nitrogen in a zeolite molecular sieve. The oxygen-rich product gas is breathed by the aircrew for the prevention of hypoxia at high altitudes. When compared to conventional liquid oxygen systems, MSOGS systems offer many benefits including reduced life cycle cost, reduced logistic support, increased aircraft versatility, and improved safety.

The critical component of the system is the oxygen concentrator which separates oxygen from the aircraft engine bleed air (compressed air) by pressure swing adsorption technology. Nitrogen is preferentially adsorbed in the molecular sieve at moderate pressures (nominal 35 psig), thereby concentrating oxygen which is collected and provided to the aircrew. Subsequently, the nitrogen is released to the ambient atmosphere as a waste gas. Control of the oxygen concentration is accomplished by either diluting the product gas with cabin air or by varying one of the concentrator operating parameters such as cycle time. The concentrator need only be supplied engine bleed air and a small amount of electrical power to produce a continuous stream of concentrated oxygen. See OBOGS entry (below).

**Multi-RAE –** A chemical/gas detection and monitoring system produced by RAE Systems. It is capable of reading substance amounts at the parts-per-billion level. MultiRAE detection systems were installed in F-22 test aircraft during the F-22 aircraft oxygen generation test program to help detect any contaminants.

**MV-22/CV-22 –** The Bell-Boeing V-22 Osprey is a multi-mission, military, tilt rotor aircraft with both a vertical and short takeoff and landing capability. It is designed to perform

missions like a conventional helicopter with the long-range, high-speed cruise performance of a turboprop aircraft. The V-22 is used by the US Air Force (CV-22) and the US Marine Corps (MV-22).

**Neuro-protective –** The effect of any chemical, biological molecule, or medical practice which has a protective effect in the nervous system against neurodegenerative disease, toxins, or brain injury.

**Neurotoxicity –** Occurs when exposure to natural or artificial toxic substances (neurotoxins) alters the normal activity of the nervous system in such a way as to cause damage to nervous tissue. This can include disruption or the death of neurons, which are key cells that transmit and process signals in the brain and other parts of the human nervous system. Symptoms may appear immediately after exposure or be delayed.

**Nitrogen –** A chemical element that is a colorless, odorless, tasteless, and mostly inert gas at standard conditions. It constitutes about 78 percent of the Earth's atmosphere by volume. Many industrially important compounds, such as ammonia, nitric acid, organic nitrates (propellants and explosives), and cyanides, contain nitrogen. It also occurs in all living organisms, primarily in amino acids and thus proteins. The human body contains about 3% by weight of nitrogen.

**Non Developmental Item –** Any previously developed item of supply used exclusively for government purposes by a Federal Agency, a State or Local Government, or a Foreign Government with which the United States has a mutual defense cooperation agreement. It also includes any item described above that requires only minor modifications or modifications of the type customarily available in the commercial marketplace in order to meet the requirements of the procuring department or agency.

**No Observed Adverse Effect Level –** In toxicology it is specifically the highest tested dose or concentration of a substance at which no measureable adverse effect is found in exposed test organisms where higher doses or concentrations resulted in an adverse effect.

**On-Board Oxygen Generation System (OBOGS) –** An OBOGS generates oxygen enriched air directly and in unlimited amounts on board aircraft to meet all the physiological needs (including breathable gas and anti-g protection) for the aircrew. An OBOGS can provide significant advantages over a stored-oxygen system (using either gaseous or liquid oxygen). In general an OBOGS requires much less maintenance than a comparable stored-gas system and does not have to be periodically replenished with oxygen. Rather, as long as the aircraft engines operate normally a steady supply of breathable, oxygen-rich air is provided. In an OBOGS an adsorbent is used to remove nitrogen from the air, which in turn enriches the oxygen concentration in the outlet air stream. Materials such as zeolite are commonly used to remove nitrogen and concentrate oxygen. See the Molecular Sieve Oxygen Generating Systems entry.

**Operational Test and Evaluation –** The field test, under realistic conditions, of any item (or key component) of weapons, equipment, or munitions for the purpose of determining the effectiveness and suitability of the weapons, equipment, or munitions for use in combat by typical military users; and the evaluation of the results of such tests.

**Organic Polymer –** A polymer is any of various chemical compounds made of smaller, identical molecules (called monomers) linked together. Organic polymers are carbon-based.

Some organic polymers, like cellulose, occur naturally, while others, like nylon, are artificial. Polymers have extremely high molecular weights, make up many of the tissues of organisms, and have extremely varied and versatile uses in industry, such as in making plastics, concrete, glass, and rubber.

**Organophosphate –** The general name for esters of phosphoric acid. Many organophosphates are widely used as solvents, plasticizers, and extreme pressure additives to some lubricants (where they decrease wear of the parts of the gears exposed to very high pressures). However, organophosphates are also the basis of many insecticides, and herbicides. Many organophosphates are highly toxic and even at relatively low levels may be hazardous to human health.

**Oxygen Saturation –** Oxygen saturation (also known as dissolved oxygen) is a relative measure of the amount of oxygen that is dissolved or carried in a given medium. It can be measured with a dissolved oxygen probe such as an oxygen sensor. In medicine, oxygen saturation refers to oxygenation, or when oxygen molecules enter the tissues of the body. In this case blood is oxygenated in the lungs, where oxygen molecules travel from the air and into the blood. Oxygen saturation measures the percentage of hemoglobin binding sites in the bloodstream occupied by oxygen molecules.

**Packard Commission –** The President's Blue Ribbon Commission on Defense Management (also known as the Packard Commission) was commissioned to study several areas of management functionality within the Department of Defense. Chaired by David Packard, the Commission made several recommendations: (1) that defense appropriations should be passed by the United States Congress in two-year budgets rather than annual appropriations bills; (2) the creation of a "procurement czar," to be known as the Under Secretary of Defense for Acquisition and the creation of a clear hierarchy of acquisition executives and managers in each of the Services; (3) the Theater Commanders (today's Combatant Commanders) should report directly to the Secretary of Defense through the Chairman of the Joint Chiefs of Staff; and (4) the powers of the Chairman of the Joint Chiefs of Staff should be strengthened. Many of the recommendations by the commission were used when Congress passed the Goldwater-Nichols Act. See the entry for Goldwater-Nichols.

**Partial Pressure, Partial Pressure of Oxygen –** The individual pressure exerted independently by a particular gas within a mixture of gases is the "partial pressure" of that gas. The air breathed by those residing within earth's biosphere is mixture of gasses (primarily nitrogen, oxygen, argon, and carbon dioxide). The total pressure generated by the air is due in part to nitrogen, in part to oxygen, and in part to each of the other constituent gases that make up the atmosphere. That part of the total pressure generated by oxygen is the "partial pressure" of oxygen. When the partial pressure of oxygen falls too low (caused by increasing altitude, in which the partial pressure of all the constituent gases falls; or without increasing altitude, by the percentage of oxygen in the surrounding air being reduced through some means) then humans suffer ill effects, the alleviation or prevention of which requires the provision of adequate amounts of supplemental breathing oxygen.

**Permissible Exposure Limit –** The permissible exposure limit (PEL) is a regulatory limit for exposure of a worker to a chemical substance or physical agent. For chemicals, the limit is usually expressed in parts per million (ppm). Permissible exposure limits are

established by the Occupational Safety and Health Administration. A PEL is usually given as a time-weighted average (TWA), although some are short-term exposure limits. A TWA is the average exposure over a specified period of time, usually a nominal eight hours. This means that, for limited periods, a worker may be exposed to concentrations higher than the PEL, so long as the average concentration over eight hours remains lower. In contrast, a short-term exposure limit is one that addresses the average exposure over a 15-30 minute period of maximum exposure during a single work shift.

**Petroleum, Lubricants, and Oils (POL) –** A term sometimes used as a “shorthand” for the totality of petroleum derived products used on an aircraft, including jet fuel, engine oil, lubricating oils, some coolants, etc.

**Phosphorylated Butylcholinesterase (BChE)** – Butyrylcholinesterase (BChE) is an enzyme that hydrolyses many different choline esters. Detection of phosphorylated BChE in human plasma can serve as an exposure biomarker of exposure to organophosphate pesticides and nerve agents.

**Plenum, Plenum Chamber –** A pressurized housing containing a gas or fluid (typically air) at positive pressure (pressure higher than surroundings). The function of the plenum is often to equalize pressure for more even distribution, because of irregular supply or demand. For an OBOGS-type aircraft breathing system, the existence of and size of the plenum can determine the amount of residual breathing oxygen/air available to the aircrew in the event of an interruption of the primary gas supply stream feeding the plenum.

**Poly-Alpha-Olefin (PAO) –** PAO is a polymer made by polymerizing an alpha-olefin. An alpha-olefin (or α-olefin) is an alkene where the carbon-carbon double bond starts at the α-carbon atom, i.e., the double bond is between the #1 and #2 carbons in the molecule. Many poly-alpha-olefins do not crystallize or solidify easily and are able to remain oily, viscous liquids even at lower temperatures. Low molecular weight poly-alpha-olefins are useful as synthetic lubricants such as synthetic motor oils for vehicles used in a wide temperature range, including aircraft jet engines.

**ppbRAE –** A very sensitive device manufactured by RAE Systems for measuring volatile organic compounds (VOCs). It is capable of sensing VOC concentrations measured as low as one part per billion. It is used for various hazardous materials, Homeland Security, industrial hygiene, indoor air quality, and military applications.

**Pressure Breathing for G –** A system/technique where the beneficial effects and actions of an anti-G suit is augmented by a small amount of pressure applied to the lungs (i.e., partial pressure breathing), which also enhances resistance to the high G-loads experienced by aircrew in some 4$^{th}$ and 5$^{th}$ generation fighters (e.g., the F-22 Raptor and F-35 Lightning II).

**Pressure Swing Adsorption (PSA) –** A technology used to separate some gas species from a mixture of gases under pressure according to the species’ molecular characteristics and affinity for an adsorbent material. Special adsorptive materials (e.g., zeolites) are used as a molecular sieve, preferentially adsorbing the target gas species at high pressure. The process then swings to low pressure to desorb the adsorbent material. Pressure swing adsorption processes rely on the fact that under high pressure, gases tend to be attracted

to solid surfaces, or "adsorbed." The higher the pressure, the more gas is adsorbed; when the pressure is reduced, the gas is released, or desorbed. If a gas mixture such as air, for example, is passed under pressure through a vessel containing an adsorbent bed of synthetic zeolite that attracts nitrogen more strongly than it does oxygen, part or all of the nitrogen will stay in the bed, and the gas coming out of the vessel will be enriched in oxygen. When the bed reaches the end of its capacity to adsorb nitrogen, it can be regenerated by reducing the pressure, thereby releasing the adsorbed nitrogen. It is then ready for another cycle of producing oxygen enriched air. Using two or more adsorbent vessels allows near-continuous production of the target gas.

**Press-To-Test –** A device controller (switch, button, etc.) designed so that when pressed it activates a test sequence and then reports to the operator (via noise, light, or other signal) on the current functionality of the device to which it is connected.

**Product Gas –** With respect to the F-22 OBOGS the product gas is that produced and measured at the outlet of the OBOGS. Nominally, when the OBOGS is being commanded to produce the maximum amount of oxygen of which it is capable, the product gas should consist almost exclusively of oxygen, argon, and other trace amounts of inert gases. As the OBOGS is commanded to produce a lesser percentage of oxygen the product gas would have commensurately higher percentages of nitrogen.

**Program 6, Program 8 –** Within the Department of Defense various broad categories of program spending are divided into "Major Force Programs" or MFPs. An MFP is an aggregation of Service and other component budget program elements that contain the resources required to achieve an objective or plan. It also reflects the fiscal year time-phasing of mission objectives to be accomplished and the means proposed for their accomplishment. All DoD funding resides in one of eleven MFPs. "Program 6" refers to the Research and Development budget. "Program 8" refers to the budget for Training, Medical, and Other General Personnel Activities. Other examples include Program 1 (Strategic Forces), Program 2 (General Purpose Forces), and Program 11 (Special Operations Forces).

**Program Budget Decision (PBD) –** Each budget year, many PBDs are issued by the Office of the Secretary of Defense. These PBDs modify the Military Services' suggested budgets (sometimes increasing resource allocations but, more often, reducing them). Once all of the PBDs are issued and resolved with the Services, the DoD budget is submitted to the Congress as a part of the President's Budget.

**Program Executive Officer –** A key individuals in the DoD acquisition process. A Program Executive Officer (PEO) may be responsible for a specific program (e.g., the F-35), or for an entire portfolio of similar programs. Examples include the Air Force PEO for Space, who is responsible for all acquisition programs at the Air Force Space Command's Space and Missile Systems Center and the Navy PEO for Aircraft Carriers. In general, the System Program Manager reports to the Program Executive Officer who in turn reports to the Service Acquisition Executive.

**Program Objective Memorandum (POM) –** The final product of the DoD Components' internal programming processes, the POM is submitted to the Secretary of Defense (SecDef) by the DoD Component heads (including the Secretary of the Air Force). The USAF POM recommends the USAF's total resource requirements and programs within

the parameters of SecDef's fiscal guidance and shows programmed needs for the six years of the Future Years Defense Program (FYDP) (i.e., in FY 2010, POM 2012-2017 was submitted). The SecDef responds to the Component POMs by approving them, although subject to (many) directed modifications. After an iterative process between the Components and the Office of the Secretary of Defense regarding those modifications, the POM, as modified, becomes the Components' budgets that are submitted to SecDef and then to the Congress by the President.

**Pyrolysis, Pyrolysis Product –** The thermochemical decomposition of organic material at elevated temperatures without the participation of oxygen. Pyrolysis differs from other high-temperature processes like combustion and hydrolysis in that it does not involve reactions with oxygen, water, or any other reagents. In practice, it is not possible to achieve a completely oxygen-free atmosphere and because some oxygen is present in any pyrolysis system, a small amount of oxidation occurs. Depending on the formulation of the organic material(s) undergoing pyrolysis, a wide variety of potentially harmful breakdown substances could be generated.

**Pulse Oximetry, Pulse Oximeter –** Pulse oximetry is a non-invasive method allowing the monitoring of the oxygenation of a person's hemoglobin. A pulse oximeter is a device that indirectly monitors the oxygen saturation of the blood (as opposed to measuring oxygen saturation directly through a blood sample). It also measures the pulse rate. It is used to assess real-time oxygenation and determining the need for supplemental oxygen. A pulse oximeter can provide an instantaneous readout only or also record oxygen level/pulse rate over a period of time (hours/days). Most pulse oximeters are attached to a person's finger. Some caution should be used in interpreting results when attempting to use a finger-mounted oximeter as a proxy for brain oxygenation, as sometimes accuracy can be affected by hand/finger movement or reduced limb circulation due to tight fitting equipment/clothing or cold temperatures. A recording pulse oximeter (finger mounted) is used by all F-22 pilots to provide an instantaneous indication of possible reduced oxygenation and also by medical personnel (post flight) to detect and analyze possible reduced oxygenation events/periods, whether or not noticed by the pilot at the time.

**Quadrennial Defense Review (QDR) –** A legislatively-mandated review of the US Department of Defense (DoD) strategies and priorities that is conducted every four years by the DoD. The QDR sets a long-term course for the DoD as it assesses priorities and challenges that the United States faces. It rebalances the DoD's strategies, capabilities, and forces to address current conflicts and future threats. The Quadrennial Defense Review Report is the main public document describing the military doctrine of the United States.

**Raptor Cough –** A condition characterized by a repetitive, "dry" (unproductive) cough, experienced by a relatively large percentage of F-22 Raptor pilots after flights.

**Safety Critical –** A term applied to a condition, event, operation, process, or item of whose proper recognition, control, performance, or tolerance is essential to safe system operation or use; e.g., safety-critical function, safety-critical path, safety-critical component/item. See the safety critical component/item entry.

**Safety Critical Component/Item –** Any Safety Significant Item (see below) whose failure alone may result in death or loss of system (air vehicle). This includes any part, an assembly, installation equipment, launch equipment, recovery equipment, or support equipment for

an aircraft or aviation weapon system if the part, assembly, or equipment contains a characteristic any failure, malfunction, or absence of which could cause (1) a catastrophic or critical failure resulting in the loss of or serious damage to the aircraft or weapon system; (2) an unacceptable risk of personal injury or loss of life; or (3) an uncommanded engine shutdown that jeopardizes safety. Fracture critical and fatigue critical parts/assemblies are examples of specific characteristics that would cause an item to be considered as safety critical.

**Safety Critical Function –** A function which, if performed incorrectly or not performed, may result in death, loss of system (such as an air vehicle), severe injury, severe occupational illness, or major system damage. Many safety critical components/items and safety significant items will contribute to a safety critical function.

**Safety Investigation Board (SIB) (Class A, Class E) –** Following a mishap, separate safety and accident investigations are conducted. Safety investigations are conducted to prevent future mishaps. Safety investigations of weapons systems also assess possible force-wide implications on the combat readiness of these systems. By contrast, accident investigations are conducted to provide a report for public release. Safety investigations take priority over accident investigations because of the need to quickly assess the impact on a weapons system's ability to fulfill its national defense role. The SIB is convened within days of the mishap and is given approximately thirty days to return its assessment. The SIB Report is prepared in two parts. The first is purely factual, and the second is privileged, meaning it is to be used solely for mishap prevention and is restricted from release outside the Air Force. The factual part is passed to the accident investigation board and is incorporated in that report in its entirety. The privileged part contains testimony taken under promise of confidentiality and a record of the SIB's deliberations.

Mishaps (and the SIBs that investigate them) are categorized by the severity of the mishap results. With regard to the SAB's F-22 Aircraft Oxygen Generation Study there have been two mishap types of interest.

Class A: A mishap resulting in (1) direct mishap cost totaling $2,000,000 or more, (2) a fatality or permanent total disability, and/or (3) the destruction of a DoD aircraft. The SIB that investigated the 2010 fatal crash of an F-22 Raptor in Alaska was a Class A Safety Investigation Board.

Class E: Events that do not meet reportable mishap classification criteria but nonetheless had a high potential for causing injury, occupational illness, or damage. Class E events are deemed important to investigate and trend for mishap prevention. Examples include unintentional departure from controlled flight, jet engine flameouts, loss of flight instruments, physiological events, etc. In general, these events may have been resolved without the loss or damage to an aircraft and without aircrew injury but the potential for one or both did exist. The (to date) two SIBs (one convened by Air Combat Command and one by Pacific Air Forces) that have examined the series of hypoxia incidents in the F-22 Raptor have been Class E Safety Investigation Boards.

**Safety of Flight –** A safety of flight item is one whose failure could cause loss of an aircraft or aircrew, or cause inadvertent store release. A loss could occur either immediately upon failure or subsequently if the failure remained undetected.

**Safety Significant –** When used to qualify an object, such as a system, structure, component, or accident sequence, this term identifies that object as having an impact on safety, whether determined through risk analysis or other means, which exceeds a predetermined significance criterion.

**Safety Significant Item –** An item which contributes to a safety critical function.

**Short Term Exposure Limit (STEL) –** A term used in occupational health, industrial hygiene, and toxicology. The STEL may be a legal limit in the United States for exposure of a worker to a chemical substance. The Occupational Safety and Health Administration has set STELs for many substances. For chemicals, STEL assessments are usually done for 15 minutes and expressed in parts per million. Usually a short-term exposure limit addresses the average exposure over a 15-30 minute period of maximum exposure during a single work shift.

**Spirometry –** A common pulmonary function test that measures lung function, specifically the amount (volume) and/or speed (flow) of air that can be inhaled and exhaled. Spirometry is used in assessing conditions such as asthma, pulmonary fibrosis, and cystic fibrosis. The spirometry test is performed using a device called a spirometer. The test is highly dependent on patient cooperation and effort, and is normally repeated at least three times to ensure reproducibility.

**Summa Canister –** A stainless steel electro-polished (or "summa" polished) passivated vacuum vessel used to collect a whole air sample. To collect a sample, the summa canister valve is opened and the canister is left in a designated area for a period of time (sometimes very short, to "grab" an air sample) to allow the surrounding air to fill the canister and achieve a representative sample. The valve is then closed and the canister is sent to a laboratory for analysis.

**System Program Office (SPO) –** A Department of Defense system program office normally is responsible for the development, acquisition, and support of a weapon system. It provides program direction and logistics support as the single face to the customer. Among other tasks, a SPO is responsible for acquisition, systems engineering and depot repair support; manages equipment spares; provides storage and transportation; and accomplishes modifications and equipment replacement to maintain the weapons system throughout its life. The SPO is headed by the System Program Manager and is the single Point of Contact with industry, government agencies, and other activities participating in the system acquisition and sustainment processes.

**Systems Engineering –** An interdisciplinary field of engineering that focuses on how complex engineering projects should be designed and managed over the life cycle of the system. Issues such as logistics, the coordination of different teams, and automatic control of machinery become more difficult when dealing with large, complex projects. "Systems engineering," in this sense of the term, refers to the distinctive set of concepts, methodologies, organizational structures, etc., that have been developed to meet the challenges of engineering very complex functional physical systems.

**T-6 –** The T-6 Texan II is a two-seat aircraft that is used by the US Air Force and US Navy to perform primary flight training for new pilots and weapon system operators. The T-6 is

powered by a single turbo-prop engine and utilizes an OBOGS system for production of breathing oxygen for the crew.

**Temporary Emergency Exposure Limit (TEEL) –** TEELs are guidelines designed to predict the response of members of the general public to different concentrations of a chemical during an emergency response incident. TEELs estimate the concentrations at which most people will begin to experience health effects if they are exposed to a hazardous airborne chemical for a given duration. TEELs have been established for over 3,000 chemicals. A chemical may have up to three TEEL values, each of which corresponds to a specific tier of health effects:

- **TEEL-3** is the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience life-threatening adverse health effects or death.
- **TEEL-2** is the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting, adverse health effects or an impaired ability to escape.
- **TEEL-1** is the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience notable discomfort, irritation, or certain asymptomatic, non-sensory effects. However, these effects are not disabling and are transient and reversible upon cessation of exposure.

**Terms of Reference –** A statement of the background, objectives, and purpose of a program, project, or proposal which shows how the scope will be defined, developed, and verified.

**Thermal Transport Medium –** A substance used to transfer heat energy from one location to another in a system. For example, in an automobile, radiator coolant (sometimes water) is used to move excess heat from the engine block to the radiator where it can be transferred to the atmosphere.

**Threshold Limit Value (TLV) –** A level to which it is believed a worker can be exposed day after day for a working lifetime without adverse health effects. It is an estimate based on the known toxicity in humans of a given chemical substance. The TLV for chemical substances is defined as a concentration in air, typically for inhalation or skin exposure.

**Toxicity –** Toxicity is the degree to which a substance can be poisonous. The toxicity of a substance is normally dose-dependent; even water can lead to water intoxication when taken in large enough doses, whereas for even a very toxic substance (e.g., cyanide) there is a dose below which there is no detectable toxic effect. Toxicity of a substance can be affected by many different factors, such as the pathway of administration (whether the toxin is applied to the skin, ingested, inhaled, or injected), the time of exposure (acute, intermediate or chronic exposure), the number of exposures (a single dose or multiple doses over time), the physical form of the toxin (solid, liquid, or gas), the genetic makeup of an individual, an individual's overall health, and many others.

**Toxic Level of Contaminant –** A level of a given contaminant that is likely to produce a defined degree of biological harm within a specified period of exposure.

**TOXLINE –** A toxicology database that provides bibliographic information covering the biochemical, pharmacological, physiological, and toxicological effects of drugs and other chemicals. It contains over 4 million bibliographic citations.

**TOXNET –** The TOXicology Data NETwork is a cluster of databases covering toxicology, hazardous chemicals, environmental health, and related areas. TOXNET provides free access to and easy searching of a large number of toxicology databases.

**Tricresyl Phosphate (TCP) –** An organophosphate compound that is a colorless, viscous liquid that is almost insoluble in water. TCP is used as a plasticizer and in many other applications including as a hydraulic fluid and a heat exchange medium. It is also used as an additive in turbine engine oil.

**Volatile Organic Compound (VOC) –** VOCs are chemicals (both naturally occurring and man-made) with a high vapor pressure at room-temperature conditions. Their high vapor pressure results from a low boiling point, which causes large numbers of molecules to evaporate from the liquid or solid form of the compound and enter the surrounding air. Many VOCs are dangerous to human health or cause harm to the environment at high concentrations.

**Work Breakdown Structure (WBS) –** A decomposition of a program/project into smaller components that defines and groups a project's discrete work elements in a hierarchy of levels that helps organize, rank by level, and define the total work scope of the project. A WBS element may be a product, data, rank by level, a service, or any combination. A WBS also provides the necessary framework for detailed cost estimating and control along with providing guidance for schedule development and control.

**Zeolite –** Zeolites are microporous, aluminosilicate solids commonly used as commercial adsorbents. They are also known as "molecular sieves." The term molecular sieve refers to a particular property of these materials, i.e., the ability to selectively sort molecules based primarily on a size exclusion process. Zeolites are widely used as ion-exchange beds in domestic and commercial water purification, softening, and other applications. In chemistry, zeolites are used to separate molecules (only molecules of certain sizes and shapes can pass through), and as traps for molecules so they can be analyzed. Zeolite-based oxygen concentrator systems are widely used to produce medical-grade oxygen. The zeolite is used as a molecular sieve to create purified oxygen from air using its ability to trap impurities, in a process involving the adsorption of nitrogen, leaving highly purified oxygen and up to 6% argon. OBOGS use synthetic zeolites to remove nitrogen from compressed air in order to supply oxygen for aircrews at high altitudes. This leaves an oxygen-rich mixture (up to 94% oxygen plus about 6% argon, an inert gas).

**Zirconia Oxygen Sensor –** An electronic device that measures the proportion of oxygen in the gas being analyzed. They are used for oxygen monitoring and control purposes. The sensing element is made with a zirconia ceramic coated on both the sensing and reference sides with a thin layer of platinum. The most common application is to measure the exhaust gas concentration of oxygen for internal combustion engines in automobiles and other vehicles. Divers and other users for whom percentage of oxygen is very important also use a similar device to measure the partial pressure of oxygen in a breathing gas.

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# Appendix M: Acronyms and Abbreviations

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|---|---|
| **@** | At |
| **&** | And |
| **%** | Percent |
| **#** | Number |
| **$** | Dollars |
| **'** | Feet |
| **µ** | Micro |
| **µg/m3** | Micrograms per Cubic Meter |
| **1FW** | 1st Fighter Wing |
| **9th AF/SE** | 9th Air Force Directorate of Safety |
| **59th MDTS** | 59th Diagnostics and Therapeutics Squadron |
| **AB** | Afterburner |
| **A/C, a/c** | Aircraft |
| **ACC** | Air Combat Command |
| **ACGIH** | American Conference of Industrial Hygienists |
| **ACH** | Analysis of Competing Hypotheses |
| **ACM** | Air Cycle Machine |
| **ACS** | Assistant Chief of Staff |
| **AETC** | Air Education and Training Command |
| **AETC/A3** | Air Education and Training Command's Directorate of Intelligence, Operations and Nuclear Integration |
| **AETC/SG** | Air Education and Training Command's Office of the Surgeon General |
| **AF/A3/5** | Air Force Deputy Chief of Staff for Air, Space, and Information Operations, Plans and Requirements |
| **AF/A4/7** | Air Force Deputy Chief of Staff for Logistics, Installations, and Mission Support |
| **AF/A5R** | HQ USAF Director of Operational Capability Requirements |
| **AF/A9** | HQ USAF Directorate of Studies & Analyses, |

| | |
|---|---|
| | Assessments and Lessons Learned |
| **AFB** | Air Force Base |
| **AF/CC-SA** | Special Assistant to the AF Chief of Staff |
| **AFETS** | Air Force Engineering and Technical Services |
| **AFFTC** | Air Force Flight Test Center |
| **AFHSIO** | Air Force Human Systems Integration Office |
| **AFI** | Air Force Instruction |
| **AFIT** | Air Force Institute of Technology |
| **AF/JA** | Air Force Judge Advocate General |
| **AFLCMC** | Air Force Life Cycle Management Center |
| **AFMC** | Air Force Materiel Command |
| **AFMC/EN** | AFMC Directorate of Engineering and Technical Management |
| **AFMC/ENS** | Systems Engineering Division of the AFMC Directorate of Engineering and Technical Management |
| **AFMC/SE** | Air Force Material Command Director of Safety, AFMC Directorate of Safety |
| **AFMC/SG** | Air Force Materiel Command Surgeon General, Office of the AFMC Surgeon General |
| **AFRes** | Air Force Reserve |
| **AFRL** | Air Force Research Laboratory |
| **AFSC** | Air Force Safety Center |
| **AFSC** | Air Force Specialty Code |
| **AFSC/SEF** | AF Safety Center, Aviation Safety Division |
| **AF/SG** | Air Force Surgeon General, Office of the AF Surgeon General |
| **AF/ST** | Air Force Chief Scientist, Office of the AF Chief Scientist |
| **AGL** | Above Ground Level |
| **AGCAS** | Automatic Ground Collision Avoidance System |
| **AIP** | Acquisition Improvement Program |
| **AL** | Armstrong Laboratory |
| **Alpha** | Angle-of-Attack |
| **AMDS** | Aerospace Medicine Squadron |

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|---|---|
| **AMXS** | Aircraft Maintenance Squadron |
| **AOG** | Aircraft Oxygen Generation |
| **AOG** | Air Operations Group |
| **APOM** | Amended Program Objective Memorandum |
| **Apr** | April |
| **APU** | Auxiliary Power Unit |
| **AR, Ar** | Argon |
| **ARC** | Air Recharge Compressor |
| **ARIP** | Advanced Medium-Range Air-to-Air Missile (AMRAAM) Vertical Eject Launcher (*A*VEL) *R*eplacement *I*nstrumentation *P*ackage (ARIP) |
| **A/S** | Airspeed |
| **ASBREM** | Armed Services Biomedical Research Evaluation and Management |
| **ASC** | Aeronautical Systems Center |
| **ASCC** | Air Standardization Coordinating Committee |
| **ASD** | Aeronautical Systems Division |
| **ASHRAE** | American Society of Heating, Refrigerating and Air Conditioning Engineers |
| **ASIC** | Air and Space Interoperability Council |
| **ATAGS** | Advanced Technology Anti-Gravity Suit |
| **ATF** | Advanced Tactical Fighter |
| **Aug** | August |
| **AUTO, Auto** | Automatic |
| **B** | Billion |
| **BAR** | Broad Area Review |
| **BFM** | Basic Fighter Maneuvers |
| **BIT** | Built-In-Test |
| **BOS** | Backup Oxygen System |
| **BRAC** | Base Realignment and Closure |
| **BRAG** | Breathing Regulator/Anti-G |
| **Brig Gen** | Brigadier General |
| **CA** | California |
| **CA** | Cabin Altitude |

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|---|---|
| **Capt** | Captain |
| **CFD** | Computational Fluid Dynamics |
| **Chem/Bio** | Chemical/Biological |
| **$C_i$** | Maximum Measured Concentration of Each Chemical |
| **CLSS** | Contractor Logistics Sustainment and Support |
| **CNS** | Central Nervous System |
| **Co** | Company |
| **CO** | Colorado |
| **CO** | Carbon Monoxide |
| **CO2, $CO_2$** | Carbon Dioxide |
| **Col** | Colonel |
| **Conc** | Concentration |
| **Config** | Configuration |
| **COTS** | Commercial Off the Shelf |
| **CPK** | Coburn, Foster, & Kane |
| **CRU** | Crew Regulator Unit |
| **CSAF** | Chief of Staff of the Air Force |
| **CTF** | Combined Test Force |
| **Cu/in** | Cubic Inches |
| **DAB** | Defense Acquisition Board |
| **DC** | District of Columbia |
| **DCS** | Deputy Chief of Staff |
| **Dec** | December |
| **deg** | Degree, Degrees |
| **Dem/Val** | Demonstration/Validation |
| **DNA** | Deoxyribonucleic Acid |
| **DoD, DOD** | Department of Defense |
| **DoDD** | Department of Defense Directive |
| **DoDI** | Department of Defense Instruction |
| **DoE** | Department of Energy |
| **Dr** | Doctor |
| **DSTO** | Defence Science and Technology Organization |
| **DTC** | Data Transfer Cartridge |

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|---|---|
| **D-Tube** | Desorption Tube |
| **EBIT** | Extended Built In Test |
| **ECS** | Environmental Control System |
| **Ed, ed., eds.** | Editor, Editors |
| **e.g.** | For Example |
| **Elmo** | Elmendorf Air Force Base |
| **EMD** | Engineering and Manufacturing Development |
| **EOS** | Emergency Oxygen System |
| **EPA** | Environmental Protection Agency |
| **ESOH** | Environment, Safety, and Occupational Health |
| **ETR** | Engine Thrust Request |
| **F** | Fahrenheit, degrees Fahrenheit |
| **FAA** | Federal Aviation Administration |
| **FAR** | Federal Acquisition Regulations |
| **FFRDC** | Federally Funded Research and Development Center |
| **FL** | Flight Level |
| **FL** | Florida |
| **FMECA** | Failure Mode Effects and Criticality Analysis |
| **FOC** | Full Operational Capability |
| **FOT&E** | Follow-On Test and Evaluation |
| **FOUO** | For Official Use Only |
| **FRP** | Full Rate Production |
| **FS** | Fighter Squadron |
| **ft** | Feet, Foot |
| **FW** | Fighter Wing |
| **FY** | Fiscal Year |
| **g** | gram |
| **G, g** | Gravity, Force of Gravity |
| **GA** | Georgia |
| **GABA** | Gamma-Aminobutyric Acid |
| **Gamma** | Flight Path Angle |
| **GAO** | Government Accountability Office |
| **GCAS** | Ground Collision Avoidance System |

| | |
|---|---|
| **Gen** | General |
| **Govt** | Government |
| **GPS** | Global Positioning System |
| **H2O, $H_2O$** | Water |
| **HAF** | Headquarters United States Air Force |
| **Hg** | Mercury |
| **HIL** | Hardware-in-the-Loop |
| **HOX** | High Pressure Oxygen |
| **HPOX** | High Pressure Oxygen |
| **HPW** | Human Performance Wing |
| **HPWE** | High Pressure Water Extractor |
| **HRS** | Hours |
| **HSC** | Human Systems Center |
| **HSI** | Human Systems Integration |
| **HSIO** | Human Systems Integration Office |
| **HX** | Heat Exchanger |
| **ICAW** | Integrated Caution/Advisory/Warning |
| **ICAWS** | Integrated Caution/Advisory/Warning System |
| **ID** | Identify |
| **In, in** | inch, inches |
| **Inc** | Incorporated |
| **INC, Inc** | Increment |
| **IOC** | Initial Operational Capability |
| **IOT&E** | Initial Test and Evaluation |
| **IPT** | Integrated Product Team |
| **ITAR** | International Traffic in Arms Regulations |
| **ITB** | Integrated Terminal Block |
| **JPO** | Joint Program Office |
| **JSF** | Joint Strike Fighter |
| **K** | Thousand |
| **KCAS** | Knots Calibrated Air Speed |
| **KIO** | Knock It Off |
| **LAB** | Line Abreast |

| | |
|---|---|
| **LED** | Light Emitting Diode |
| **LOX** | Liquid Oxygen |
| **lpm** | Liters per Minute |
| **LPWE** | Low Pressure Water Extractor |
| **LRIP** | Low Rate Initial Production |
| **LSS** | Life Support System, Life Sustainment System |
| **Lt Col** | Lieutenant Colonel |
| **Lt Gen** | Lieutenant General |
| **M** | Mach Number |
| **M** | Million |
| **$m^3$** | Cubic Meter |
| **Maj** | Major |
| **Maj Gen** | Major General |
| **MAX, Max** | Maximum |
| **MBIT** | Maintenance Built In Test |
| **MCM** | Molecular Characterization Matrix |
| **MD** | Doctor of Medicine |
| **MD** | Maryland |
| **MDS** | Mission Design Series |
| **MDTS** | Diagnostics and Therapeutics Squadron |
| **MFV** | Multi Function Valve |
| **$mg/m^3$** | Milligrams per Cubic Meter |
| **MIL, Mil** | Military |
| **Mil-Spec, MIL-SPEC** | Military Specification |
| **MIL-STD, Mil-Std** | Military Standard |
| **mm** | Millimeter, Millimeters |
| **mm/Hg** | Millimeters of Mercury |
| **MPH** | Master of Public Health |
| **MPT** | Manpower, Personnel, and Training |
| **Mr** | Mister |
| **MSL** | Mean Sea Level |
| **Msn, MSN** | Mission |
| **MSOGS** | Molecular Sieve Oxygen Generating System |

| | |
|---|---|
| **MTBF** | Mean Time Between Failures |
| **MXG** | Maintenance Group |
| **MY** | Multi Year |
| **N, $N_2$** | Nitrogen |
| **N/A** | Not Applicable |
| **NASA** | National Aeronautics and Space Administration |
| **NAVAIR** | Naval Air Systems Command |
| **NAWC** | Naval Air Warfare Center |
| **n.d.** | not dated, no date |
| **NDI** | Non Developmental Item |
| **NFF** | No Fault Found |
| **NIOSH** | National Institute for Occupational Safety and Health |
| **nm** | Nautical Miles |
| **No.** | Number |
| **Nov** | November |
| **NRC** | National Research Council |
| **NTPD** | Normal Temperature and Pressure, Dry |
| **NzW** | Load Factor Normal to the Flight Path |
| **O** | Oxygen Partial Pressure |
| **O2, $O_2$** | Oxygen |
| **OBIGGS** | On-Board Inert Gas Generating System |
| **OBOGS** | On-Board Oxygen Generation System |
| **OCOSR** | Overseas Contingency Operations Supplemental Request |
| **OCR** | Office of Collateral Responsibility |
| **Oct** | October |
| **OGADS** | Oxygen Generating and Distribution System |
| **OH** | Ohio |
| **O&M** | Operations and Maintenance |
| **OPR** | Office of Primary Responsibility |
| **OSD** | Office of the Secretary of Defense |
| **OSHA** | Occupational Safety and Health Administration |
| **OT&E** | Operational Test and Evaluation |
| **OTI** | One Time Inspection |

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|---|---|
| **OUSD (AT&L)** | Office of the Under Secretary of Defense (Acquisition, Technology, and Logistics) |
| **Ox, Oxy** | Oxygen |
| **P** | Pressure |
| **PAO** | Poly-Alpha-Olefin, Polyalphaolefin |
| **$P_AO_2$** | Partial Pressure of Oxygen in Arterial Blood |
| **PB** | President's Budget |
| **PBD** | Program Budget Decision |
| **PBG** | Pressure Breathing for G |
| **PBL** | Performance Based Logistics |
| **PEL** | Permissible Exposure Limit |
| **POC** | Point of Contact |
| **POL** | Petroleum, Oil, and Lubricants |
| **POM** | Program Objective Memorandum |
| **pp** | Page, pages |
| **ppb** | Parts per Billion |
| **ppbV** | Parts per Billion by Volume |
| **ppm** | Parts per Million |
| **$PPO_2$** | Partial Pressure of Oxygen |
| **PRTV** | Production Representative Test Vehicle |
| **PRV** | Pressure Relief/Regulator Valve |
| **PSA** | Pressure Swing Adsorption |
| **PSI, psi** | Pounds per Square Inch |
| **PSID, psid** | Pounds per Square Inch Differential |
| **PSIG, psig** | Pound per Square Inch Gauge |
| **Pulse-Ox** | Pulse Oximeter |
| **PVCV** | Pressurization and Vent Control Valve |
| **PVI** | Pilot Vehicle Interface |
| **QDR** | Quadrennial Defense Review |
| **RCCA** | Root Cause Corrective Action |
| **R-D** | Rapid Decompression |
| **RDT&E** | Research, Development, Test, and Evaluation |
| **Reg** | Regulator |

| | |
|---|---|
| **Regen** | Regenerative |
| **REOS** | Regulated Emergency Oxygen System |
| **Ret** | Retired |
| **RQ** | Respiratory Quotient |
| **RTA** | Replacement Test Aircraft |
| **RTF** | Return to Fly |
| **SAB** | Scientific Advisory Board |
| **SAF** | Secretary of the Air Force, Air Force Secretariat |
| **SAF/AQ** | Assistant Secretary of the Air Force for Acquisition |
| **SAF/AQR** | Deputy Assistant Secretary of the Air Force for Science, Technology and Engineering |
| **SAF/AQX** | Deputy Assistant Secretary for Acquisition Integration |
| **SAF/FM** | Assistant Secretary of the Air Force for Financial Management and Comptroller |
| **SAF/IE** | Assistant Secretary of the Air Force for Installations, Environment, and Logistics |
| **SAF/OS** | Office of the Secretary of the Air Force |
| **SCF** | Safety Critical Function |
| **SCI** | Safety Critical Item |
| **SE** | Safety |
| **sec** | second, seconds |
| **SecAF** | Secretary of the Air Force |
| **Sep** | September |
| **SES** | Stored Energy System |
| **SES** | Senior Executive Service |
| **SG** | Surgeon General |
| **SIB** | Safety Investigation Board |
| **SMAC** | Spacecraft Maximum Allowable Concentration |
| **SN, s/n** | Serial Number |
| **SOV** | Shut-Off Valve |
| **SPEC, Spec** | Specification |
| **SPO** | System Program Office |
| **SSI** | Safety Significant Item |

| | |
|---|---|
| **S&T** | Science and Technology |
| **STANAG** | Standardization Agreement |
| **STD, Std** | Standard |
| **S/W** | Software |
| **T** | Temperature |
| **T&E** | Test and Evaluation |
| **TCE** | Trichloroethylene |
| **TCP** | Tricrysel-Phosphate |
| **TEEL** | Temporary Emergency Exposure Limit |
| **TIC** | Toxic Industrial Compound |
| **TLSS** | Tactical Life Support System |
| **TLV** | Threshold Limit Value |
| **TMM** | Thermal Management Mode |
| **T/P/O** | Temperature/Pressure/Oxygen Partial Pressure |
| **TO** | Technical Order |
| **TOCP** | Triorthocresyl Phosphate |
| **TOR, TORs** | Terms of Reference |
| **Tox** | Toxicology, Toxin |
| **TR** | Technical Report |
| **TRL** | Technology Readiness Level |
| **TSPR** | Total System Performance Responsibility |
| **TSSR** | Total System Support Responsibility |
| **TST** | Test |
| **TW** | Test Wing |
| **TWA** | Time Weighted Average |
| **TX** | Texas |
| **U.S., US** | United States |
| **USAARL** | United States Army Aeromedical Research Laboratory |
| **USAF** | United States Air Force |
| **USAFR** | United States Air Force Reserve |
| **USAFSAM** | United States Air Force School of Aerospace Medicine |
| **USMC** | United States Marine Corps |
| **USN** | United States Navy |

| | |
|---|---|
| **VA** | Virginia |
| **VADM** | Vice Admiral |
| **VOC** | Volatile Organic Compound |
| **Vs.** | Versus |
| **W/, w/** | With |
| **WAM** | Warm Air Manifold |
| **WPAFB** | Wright-Patterson Air Force Base |
| **WUT** | Wind Up Turn |
| **YF** | Prototype Fighter |
| **Zulu** | Greenwich Mean Time |

# Appendix N: Bibliography

This bibliography is a list of materials that informed the Aircraft Oxygen Generation (AOG) Study Panel members' deliberations during the course of this Study. These represent almost all of the materials (briefings, papers, articles, data, etc.) made available to members of the AOG Study during the preparation for and conduct of the Study. Many were provided by outside organizations/individuals that briefed or otherwise informed the Study Panel and some were contributed by the Panel members themselves. In general these materials were provided as background information or as briefings during various fact finding trips or meetings undertaken by the Study Panel members. Many are not available for distribution beyond the Air Force Scientific Advisory Board as they contain classified, export controlled, proprietary, safety privileged, and/or For Official Use Only (FOUO) information.

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# Appendix O: Initial Distribution

**Air Force Leadership**

SAF/OS – Secretary of the Air Force
AF/CC – Chief of Staff of the Air Force
SAF/US – Under Secretary of the Air Force
AF/CV – Vice Chief of Staff of the Air Force

**Air Force Secretariat and Staff**

SAF/AQ – Assistant Secretary (Acquisition)
SAF/CIO A6 – Chief, Information Dominance and Chief Information Officer
SAF/FM – Assistant Secretary (Financial Management and Comptroller)
SAF/GC – General Counsel
SAF/IE – Assistant Secretary (Installations, Environment, and Logistics)
SAF/IG – Inspector General
SAF/LL – Director of Legislative Liaison
SAF/PA – Director of Public Affairs
AF/CVA – Assistant Vice Chief of Staff
AF/JA – The Judge Advocate General
AF/RE – Chief of the Air Force Reserve
AF/SB – Military Director of the Scientific Advisory Board
AF/SE – Chief of Air Force Safety
AF/SG – Air Force Surgeon General
AF/ST – Chief Scientist of the Air Force
AF/TE – Director of Test and Evaluation
AF/A1 – DCS Manpower, Personnel, and Services
AF/A2 – DCS Intelligence, Surveillance, and Reconnaissance
AF/A3/5 – DCS Air Space and Information Operations, Plans and Requirements
AF/A4/7 – DCS Logistics, Installations, and Mission Support
AF/A8 – DCS Strategic Plans and Programs
AF/A9 – Director of Studies and Analyses, Assessments, and Lessons Learned
AF/A10 – Director of Strategic Deterrence and Nuclear Integration
NGB/CF – Chief of the Air National Guard

**Air Force Major Commands and Direct Reporting Units**

ACC – Air Combat Command
AETC – Air Education and Training Command
AFGSC – AF Global Strike Command
AFMC – AF Materiel Command
AFRC – AF Reserve Command
AFSOC – AF Special Operations Command
AFSPC – AF Space Command

AMC – Air Mobility Command
PACAF – Pacific Air Forces
USAFE – US Air Forces Europe
AFPA – Air Force Petroleum Agency
AFSC – Air Force Safety Center

**Combatant and Regional Commands**

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US European Command
US Joint Forces Command
US Northern Command
US Pacific Command
US Southern Command
US Special Operations Command
US Strategic Command
US Transportation Command

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Director of Defense Research and Engineering
Defense Advanced Research Projects Agency

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Assistant Secretary of the Navy (Research, Development, and Acquisition)
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**13. ABSTRACT**
There have been an increasing number of hypoxia-type incidents, especially in the F-22 Raptor aircraft, that may be related to on-board oxygen generating systems (OBOGS). This report details recommendations made by the USAF Scientific Advisory Board's Aircraft Oxygen Generation (AOG) Quicklook Study to help mitigate this safety problem. The AOG Study Panel received a large number of briefings and perspectives on various aircraft OBOGS standards and designs in general; the F-22 and F-22 OBOGS in particular, pilot physiological performance under various conditions, and many other related issues, from within and outside the United States Government. The Study Panel evaluated the current F-22 oxygen system, OBOGS and life support systems in general (including contaminants that could affect OBOGS operation), and human responses to high altitude rapid cabin altitude changes/rapid decompression environment with less than 90% oxygen. It also assisted with: F-22 return-to-fly criteria as requested, evaluation of Air Standards, review and validation of performance-based acquisition programs and associated risk analysis protocols, and with reviewing and revalidating aircrew flight equipment affiliated with OBOGS-equipped aircraft.

**14. SUBJECT TERMS**
Aircraft Oxygen Generation, AOG, Backup Oxygen System, BOS, Breathing Regulator Anti-G Valve, BRAG, Emergency Oxygen System, EOS, Environmental Control System, ECS, F-22, F-35, Human Systems Integration, HSI, Hypoxia, Life Support System, Life Sustainment System, LSS, Molecular Characterization, Molecular Sieve, On-Board Oxygen Generation System, OBOGS, Plenum, Pressure Swing Absorption, PSA, Zeolite

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